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Galileo on Scientific Explanation: His Debt to and Departure from Aristotle
and His Contributions to Contemporary Models

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Galileo on Scientific Explanation: His Debt to and Departure from Aristotle and His Contributions to Contemporary Models

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Galileo on Scientific Explanation: His Debt to and Departure from Aristotle and His Contributions to Contemporary Models

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Among the figures of the Scientific Revolution, Galileo was the most influential in moving science away from Aristotle's concept of scientific explanation to what became Modern science. My primary goal in this thesis is to explicate Galileo's concept of scientific explanation, as well as the metaphysical and methodological underpinnings relied upon by Galileo, and to investigate where these depart from Aristotle as well as the Aristotelians of Galileo's time. Galileo's most revolutionary scientific achievement was to advance a new, more practical aim for scientific inquiry: he changed the focus of scientific investigations to the measuring, modeling, and predicting of phenomena. In order to increase the reliability of his hypotheses Galileo rejected those aspects of Aristotle's account of scientific explanation that could not be rigorously empirically justified. The result was that empirical science no longer searched for the essential attributes of bodies or for Aristotle's causes such as the "final" cause. The identified contributions and innovations promulgated by Galileo are significant because they dictated changes that became formative to contemporary models of scientific explanation. I argue that analyses such as the one given in this dissertation can provide a framework for better understanding twentieth-century criticisms that argue that Aristotle's concept of scientific explanation contained elements that are indispensable to genuine scientific explanations but that are missing from standard contemporary accounts such as Hempel's covering law models. Finally, I conclude that my analysis of Galileo's contributions to scientific explanation suggests that contemporary claims that covering law models should be more receptive to Aristotle's ideas of causation and essence are misguided.

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Chapter 1. Introduction

> "Please observe, gentlemen, how facts that at first seem improbable will, even on scant explanation, drop the cloak that has hidden them and stand forth in naked and simple beauty." Galileo[1]

1.1 Introduction

I argue that the work of Galileo Galilei (1564-1642), besides teaching us about the foundations of Modern science, the direct ancestor to contemporary science, still holds lessons for contemporary philosophy of science. Wallace (1972) reports that "Galileo is almost universally regarded as the key figure in the foundation of modern science" (p. 176). Galileo's discoveries led to unprecedented scientific progress[2] by trying to match mathematical models to observational data.[3] Galileo advocated that an essential part of scientific inquiry was sharing not only his discoveries, but also his philosophy of science, which led to these discoveries.[4] His philosophy of science was revolutionary[5] and resulted in a quantum change in the purpose of scientific inquiry, toward an emphasis on

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[1] Spoken by Galileo's mouthpiece Salviati in *Two New Sciences* (1638) translated in Finocchiaro, 2008, p.297.
[2] Butterfield (1957)
[3] Newton (1687)
[4] Galileo also saw his advances in scientific methodology as paramount to his contributions to science. See Galileo's discussion in his preface to the *Dialogue* (1632); Drake says *Floating Bodies* (1612) was Galileo's most popular book in his lifetime because he was advocating a new method; *Letter to Grand Duchess Christina* (1623) talks about being careful with reasoning to what is the case. Drake (1957, p. 73f) takes pains to say that Galileo is fighting against the philosophers, not about facts but about finding truth. Drake portrays Galileo as doing 'science' and not philosophy (Drake, 1980). This is anachronistic, but perhaps helpful.
[5] Gingerich (1986: 126); Cohen (1985: 135); Butterfield (1957)

the applicability of science, which in turn led him to develop a model of scientific explanation with greater epistemic justification.

Despite all that has been written about Galileo and the Scientific Revolution, there remain misunderstandings about Galileo's contribution to scientific explanation.[6] These misunderstandings stem from a lack of clarity regarding how Galileo's concepts of scientific explanation departed from his predecessors', particularly Aristotle's (384-322 B.C.E.). This thesis examines the key differences between Galileo's concept of scientific explanation and Aristotle's. I do this to help increase our understanding of the precise changes that Galileo brought to scientific explanation and to address some of the misunderstandings regarding his influence. I propose that better understanding Galileo's contribution to scientific explanation will help to establish a framework from which to evaluate criticisms of contemporary models of scientific explanation. I argue that this framework can be used to address the specific criticisms that suggest that contemporary models of scientific explanation are missing key elements that are present in Aristotle's model.[7]

In this chapter, I introduce Aristotle's and then Galileo's ideas of scientific explanation. I then briefly introduce some of the misunderstandings about Galileo's precise contributions to scientific explanation before introducing some of the potentially relevant criticisms of contemporary scientific explanation models that would benefit from a well-explicated discussion regarding the differences between Galileo's and Aristotle's

[6] Segre (1998); Lennox (1986); Drake (1978)
[7] The criticisms made by Brody, 1972; Van Fraassen, 1980; and Salmon, 1984, of the standard contemporary model of scientific explanation are discussed below.

scientific explanations. Finally, I briefly outline the remaining four chapters of this thesis.

1.2 Aristotle, Galileo, and Key Terms

To understand Galileo's contributions to scientific explanation models, it is necessary to understand the major influences on the concept of scientific explanation that preceded Galileo. This will establish the scientific landscape upon which Galileo built his philosophy of science. Aristotle is the scientific standard bearer prior to Galileo's arrival[8]; thus we must first understand some of Aristotle's science, especially his concept of scientific explanation, before we can evaluate Galileo's achievements. To this purpose, I investigate Aristotle's ideas of scientific explanation in detail in chapter 2, but provide a brief introduction to some of his terms (i.e., scientific explanation, scientific demonstration, causation) here in order to start the conversation.

In *Posterior Analytics* I.2, Aristotle is explicit that scientific knowledge requires having the scientific explanation for a given phenomenon or event X (71b9). For Aristotle, having the scientific explanation means knowing *why* X is the case. Knowing why X is the case means being able to give a demonstration with the proper explanatory first principles in the form of a deductive syllogism that answers the question, "Why is X the case?" In *Posterior Analytics* I.13, Aristotle uses the waxing of the Moon to illustrate the difference between a deductive syllogism that merely gives a fact and a deductive syllogism that is a scientific demonstration because it answers the 'why' question:

[8] Boas Hall (1994: 216); Drake (1970: 101)

(A) all that waxes is spherical,
the Moon waxes,
thus, the Moon is spherical.

Syllogism A is a proper deduction but it only gives the fact of the matter, namely that the Moon is spherical, without answering ‘why’ the Moon is spherical. By rearranging the first premise Aristotle says it is possible to produce a scientific demonstration:

(B) all that is spherical waxes,
the Moon is spherical,
thus, the Moon waxes.

Syllogism B is a scientific demonstration, and hence an explanation, according to Aristotle because it answers why the Moon waxes, namely, because it is spherical. Sphericity is the formal cause of the Moon’s waxing.[9]

Answering ‘why’ questions is at the heart of Aristotle’s concept of causation. Surprisingly, given how important causation is to Aristotle’s scientific explanations, Drake (1981) argues that Aristotle does not define cause:

> In saying this [that Aristotle does not define cause], I rely on my understanding of *Causality and Scientific Explanation*, a two-volume survey published in 1972 by William A. Wallace, who gave the traditional meaning of *cause* as ‘something that exists outside the mind and serves to explain, not merely in a logical way, why the thing is as it is.’ Thus the notion of external existence of causes was included in any reference to them, though the determination of cause was a matter of reason rather than of direct observation. (pp. xxv-xxvi)

[9] See below for discussion of Aristotle’s “four causes”.

Drake (1981) may be right that Aristotle does not define cause in the way that Aristotle suggests definitions should be rendered. However, Aristotle describes his use of causation when he explains the four types of answers to ‘why’ questions, for instance, in *Posterior Analytics* II, *Physics* II, and *Metaphysics* V.[10]

In the *Physics* and *Metaphysics,* Aristotle explains the “four causes”: material, efficient, formal, and final. The material cause answers questions such as, “Why is the statue heavy?” (Because it is made of bronze). The efficient cause answers questions such as, “Why is there a statue?” (Because Lysistratus made it). The formal cause answers questions such as, “Why does the statue look the way it does?” (Because it is meant to honor Solon by representing his image). The final cause answers questions such as, “Why is there a statue?” (Because the town wanted to honor Solon). The final cause and formal causes are sometimes the same, or at any rate very closely linked, especially in natural kinds. In sum, for Aristotle, understanding cause is essential to scientific explanation.

Although most of the conversation about Galileo occurs in chapter 4, to begin addressing the differences between Aristotle’s concept of scientific explanation and Galileo’s concept of scientific explanation, I provide here a brief overview of Galileo’s concepts in order to introduce some of the key terms that are defined and discussed in detail later. Of Galileo’s many achievements, this thesis examines the one that underlies all the others: the advances Galileo made to scientific explanation and the tools he used to bring about these advances. For Galileo, having scientific knowledge of X means having

[10] See Hankinson (1998) p. 132 (footnote about Hocutt [1974]). Aristotle says there are four types of “*aition”,* which is usually rendered as ‘cause’, but ‘because’ has also been suggested as a closer translation.

a proper scientific explanation of X. A proper scientific explanation of X results when one can demonstrate that a model predicts phenomena (e.g., demonstrating how bodies float by giving the 'proximate' cause or demonstrating the times squared law of free fall by giving a predictive mathematical model).

For Galileo, a proximate cause is something such that if it is present, then the effect is present and if absent then the effect is absent (Drake, 1981, p.130).[11] Of Aristotle's four causes, his efficient cause is the most similar to Galileo's use of the 'proximate' cause, the difference between the two being that Galileo's use of the proximate cause often identifies a causal event, whereas Aristotle's efficient cause is predominantly an agent.

Galileo's definition of cause is not original. It is similar to the Stoic notion of the "containing" cause (*aition sunektikon)*:

> . . . causes are said to be containing if, when they are present the effect is present, when they are removed the effect is removed, and when they are decreased the effect is decreased (thus they say the application of the noose is the cause of the strangling). (Hankinson, 1998, p. 243, trans. of Sextus Empiricus, *Outlines of Pyrrhonism* 3.15).

This Stoic definition of cause described in the above quotation is very similar to Galileo's use of cause, although Galileo is not explicit about the strength or degree of effect based on degree of presence of cause.

Galileo differs from Aristotle in a fundamental way regarding what the purpose of science should be. More so than can be identified by looking at any single aspect of

[11] Galileo does not have a formal means for dealing with the apparent asymmetry problem of being able to distinguish between cause and effect, but I take up this question in greater detail in chapter four.

Galileo's method, Galileo departs both from Aristotle and from Galileo's Aristotelian contemporaries by making science about usefulness. This leads Galileo to move away from Aristotle's view of science as the search for the ultimate first principles of nature. Instead Galileo focuses on proximate causes—especially those causes that can be quantified—and on finding mathematical regularity in phenomena. Of course this change in the focus of science away from being the search for the ultimate first principles of nature toward applicability is not necessarily a matter of all or nothing, but is rather a matter of degree. Nevertheless, this represents a significant shift in focus.

Galileo's interest in the proximate cause (compared with Aristotle's interest in the final cause) reflects an interest in cause only insofar as it is useful in making his explanations applicable (e.g., *Two New Sciences*; *Floating Bodies*). This desire for science to be applicable meant that predictive models (models of *what* happens rather than *why* it happens) should be generated. To produce predictive models, Galileo dramatically increased the level of quantification in science. This increased the level of epistemic justification (the degree of empirical evidence supporting the assertions of the model) in Galileo's explanations because quantification provides a means for judging and refining the predictive accuracy of his models. In contrast Aristotle's theory of perception affirms that human beings are good at categorizing experiences because, "for although you perceive particulars, perception is of universals" (*Posterior*

Analytics II.19, Barnes, trans., 1993, 100b).[12] Being open to receiving the forms of natural objects through observation naturally leads one toward grasping the correct universal (Lear, 1988, p. 3). Hence, Aristotle did not include in his system for generating scientific explanations a means for gauging the level of epistemic justification of universals arrived at from particular experiences.

To address this new purpose of scientific explanation, Galileo made substantial scientific advancements in applying mathematics to nature and in experimentation.[13] Galileo famously said that the universe is written in the language of mathematics (*The Assayer* [1623], Drake, trans., 1957, pp. 237-8). Galileo made science more about finding ways to manipulate nature to our own ends (e.g., artillery accuracy, pendulum clock, thermoscope, longitude problem, etc.) than Aristotle, who was explicit that knowledge and wisdom are about that which is abstract, i.e. not useful (*Metaphysics* I.1).

1.3 Galileo's Accomplishments Mischaracterized

Although a lot has been written about Galileo, there remain controversies about his contribution to scientific explanation (Wallace, 1972, p. 176). There are several muddled stories that contribute to the popular misunderstanding of Galileo's scientific contributions. In many ways Galileo is the most prominent figure of the Scientific Revolution (Wallace, 1972). However, as Lennox (1986) points out, because Galileo was a transitional figure it is easy to over-exaggerate just how revolutionary his thinking was.

[12] "Particulars" refers to the individual bodies that we encounter with our senses (e.g. this thing in front of me with leaves), and "universals" refers to the general concepts that we form about the particulars (e.g. trees have leaves).
[13] By mathematics, Galileo is primarily thinking in terms of geometry (Machamer, 1998, p. 64).

The tendency is to credit Galileo with every modern innovation and to discredit the system he helped replace. Lennox (1986) and Bowler and Morus (2005) further point out that assumptions are made to the effect that anything Galileo put forward was first of all new and, second, completely contrary to the *old* system (Koyré, 1978).

Previous accounts of what is revolutionary about Galileo's work tend to emphasize one or more of the following: Galileo's use of mathematics, his use of idealization, his writing in Italian, the difference between observation and experimentation, rationalism vs. empiricism, and even Galileo's supposed atheistic agenda (Cohen, 1960, p. 201). A broader approach should look first for Galileo's purpose in order to provide a framework for understanding the various common Galileo topics in context.

To begin to understand a framework from which to evaluate Galileo's contributions it is useful to examine contemporary commentary regarding Galileo. In general, Galileo is credited with coming up with the law of the pendulum and the law of free fall, discovering that the Moon's landscape is mountainous, providing telescopic evidence that the Earth is not the only center of motion, and advancing the systematic use of the experimental method, among many other contributions (Drake, 1978). Some have gone as far as to claim that Galileo changed our very conception of nature (Butterfield, 1957; Koyré, 1978).

While Galileo's contributions to science are unquestionably tremendous, they seem to have reached mythic proportions, periodically at the expense of accuracy (Segre, 1998; Lennox, 1986). In particular, Galileo's accomplishments may be exaggerated in terms of his introduction of mathematics and experimentation to science, not to mention claims that he had a fully developed theory of inertia and mechanical dynamics (Lindberg, 1992).

At least three myths are propagated about Galileo. One says that he differed from previous thinkers by being an empiricist; that is, all of his scientific advancements originated via observation. Cohen (1960) claims that the moment that changed everything was Galileo's turning the telescope to the heavens. Cohen says this is when Galileo "recognized" planetary motion the way it actually is and that this is what led to the Copernican system being adopted. This perspective is not completely accurate because Galileo was convinced of the Copernican solar system model, or at least Copernicus' idea of the multi-fold motion of the earth, approximately fifteen years prior to his 1609 telescopic observations. That Galileo was convinced of these ideas is apparent in a letter sent from Galileo to Kepler in 1597 stating that he (Galileo) had already been a believer in Copernicus' ideas for several years (Drake, 1978, p.40). Additionally, the suggestion that Galileo's empiricism accounts for his great advances misses the fact that Aristotle was also an empiricist (Barnes, 1995).

Another myth is the exaggeration that Galileo originated experimentation (Hall, 1962). While this is not an unusual claim, it discounts the fact that prior to Galileo experimentation occurred (e.g., Grosseteste, Theodoric; this is described in greater detail in chapter 3). This characterization that Galileo originated experimentation sometimes leads to the implication that empirical observation was not important to Aristotle, such as in Drake, 1980. However, empirical observation was fundamental to Aristotle's science because he believed that all knowledge ultimately comes from observation (Barnes, 1995, p. 16).

Another exaggeration about Galileo's contributions is the suggestion that he singularly introduced mathematics to scientific explanation. For instance, Henry (2002) does not think that mathematics was used by natural philosophers in any meaningful way prior to Galileo:

> A simple but essentially accurate way of summing up what took place in the Scientific Revolution, then, is to say that the natural philosophy of the Middle Ages, which had tended to remain aloof from mathematical and more pragmatic or experiential arts and sciences, became amalgamated with these other approaches to the analysis of nature. (p. 5)

The implication is that math was not used extensively in the Middle Ages in empirical investigation. However, as will be discussed in chapter 3, from the reintroduction of Aristotle and Euclid to the Latin West in the twelfth century, mathematics was extensively used by natural philosophers such as Grosseteste, Theodoric, Jordanus of Nemore, and Nicole Oresme among others (Dugas, 1998). Similarly, this characterization that Galileo originated the use of mathematics in science sometimes leads to the implication that mathematics does not play an important role in Aristotle's empirical sciences (Feher, 1982; Annas, 1976; Mueller, 1970). However, such suggestions fail to account for Aristotle's use of mathematics in his discussions of circular motion in *Physics* IV.14 and planetary motion in *De Caelo* I.1, and in the discussion of meteorological phenomena such as the rainbow in *Meteorology* III, among others.

I bring up these myths, not to suggest that previous scholars have dramatically misunderstood Galileo's contributions, because in general the myths that I describe appear to be more exaggerations than complete misunderstandings. Rather, I bring these up to create a starting point for discussion. Removing the hyperbole and examining the actual changes between Galileo and Aristotle permits a better opportunity for understanding Galileo's realistic contributions to scientific explanation, and the value of those contributions, which in turn facilitates a better understanding of the roots of contemporary models of scientific explanation.

1.4 Purpose of this Thesis

To fully appreciate current criticisms and to avoid making the mistakes of the past it is necessary to understand the goals of scientific explanation (Cartwright, 1983). However, because those goals have changed over time, understanding the most significant steps in the progression of science can help shed light on contemporary discussions. I propose that a clearer understanding of the origins of contemporary scientific explanation models will help to develop a framework for evaluating new meaningful contributions as well as criticisms of contemporary scientific explanation models. To that end, I investigate Galileo's development of his model of scientific explanation.

My primary goal in this thesis is to explicate Galileo's concept of scientific explanation and the ways in which it diverged from what came before, most notably Aristotle's concept of scientific explanation. I use the ways in which Galileo diverged to set up a framework for examining the role that his contributions play in contemporary discussions about scientific explanation. I then use the identified contributions to argue that the innovations promulgated by Galileo are significant because they dictated changes that became formative to the methodology used in contemporary models of scientific explanation.

Although Modern and contemporary accounts of scientific explanation are far removed from Aristotle's ideas, some contemporary philosophers argue that Aristotle's ideas about causation and essence should be reintroduced to fill in gaps in contemporary accounts of scientific explanation (e.g., Brody, 1972; Salmon, 1984). Van Fraassen (1980a) argues that while it may be desirable to reintroduce some of Aristotle's ideas to contemporary models of scientific explanation, it should only be done after understanding the repercussions of doing so. To understand these repercussions, it is helpful to understand why and how those elements of Aristotle's that contemporary models are missing were removed from scientific explanation, a removal which I argue occurred at the hands of Galileo. By using the framework created from identifying differences between Galileo and Aristotle, I hope to contribute to the understanding of what the costs and benefits might be of reintroducing certain elements of Aristotle's model of scientific explanation.

1.5 Outline of the Argument

Chapter 2 examines Aristotle's concepts of scientific demonstration and explanation. This involves comparing Aristotle's stated methods with a few cases in which Aristotle applies his method (e.g. with his demonstrations concerning the rainbow and projectile motion). Chapter 2 also looks at the various role mathematics plays in Aristotle's science. Finally, chapter 2 discusses some of the problems of Aristotle's science that set the stage for later thinkers, especially Galileo.

Chapter 3 then examines a few key actors during the intervening period between Aristotle and Galileo to facilitate understanding Galileo's development. This chapter looks at the reintroduction of Aristotle's writings, especially the *Posterior Analytics,* which was translated from Arabic into Latin in the twelfth century. It further examines the concept of scientific explanation for some of Galileo's contemporaries, and how closely their concepts were tied to Aristotle's ideas of scientific explanation.

In chapter 4, I then analyze Galileo's concept of scientific explanation, which illustrates Galileo's departure from the ideas of his predecessors as well as what is revolutionary about his work. This analysis lays out Galileo's understanding of scientific explanation, showing where it is empirical and where rational. I also examine the relationship between his scientific explanation and his interest in the purpose of science in order to evaluate why these changes may have occurred. Finally, I discuss some of the consequences to Galileo's model of scientific explanation that are attributable to Galileo's interest in increasing empirical justification.

Lastly, chapter 5 summarizes the analysis of differences between Galileo and Aristotle relevant to discussions of contemporary scientific explanation models. I then use this analysis as a basis for briefly looking at contemporary discussions about scientific explanation and ask what light a more thorough understanding of Galileo's contributions to scientific explanation models can shed on these discussions. Finally, I conclude that my analysis of Galileo's contributions to scientific explanation models suggests that those contemporary proposals that claim that covering law models should be more receptive to Aristotle's ideas of causation and essence (e.g., Brody, 1972; Van Fraassen, 1980a; Salmon, 1984) are misguided.

Chapter 2. Aristotle's Concept of Scientific Explanation

2.1 Introduction

Aristotle's concept of scientific explanation was the foundation, albeit modified through the centuries, that the agents of the Scientific Revolution were revolting against. Understanding Aristotle's concept of scientific explanation will put us in a better position to explicate and evaluate Galileo's contributions to scientific methodology in general and Galileo's concept of scientific explanation in particular.[14]

To understand Aristotle's concept of scientific explanation, this chapter examines Aristotle's explicit statements about scientific explanation as well as specific instances of explanation in his corpus, the latter of which will help illustrate how closely he was able to follow his own model. In *Posterior Analytics* I.9, Aristotle observes that "It is difficult to know whether you know something or not" (Barnes, trans., 1993, 76a25). To Aristotle, knowing something about a given natural phenomenon, i.e. having a scientific explanation of that phenomenon, means that you can give the scientific demonstration of the cause of the given phenomenon.

[14] Understanding Aristotle's concept of scientific explanation will also be helpful in chapter 5 to the analysis of criticisms that claim contemporary accounts of scientific explanation lack elements that Aristotle's system captured, elements lost in the history of science: the essence and cause of the thing being explained (Brody, 1972; Salmon, 1984). Hence, to fully appreciate such criticisms, we first need to understand whether Aristotle's concept of scientific explanation does indeed capture the essence and the cause of the thing being explained. If so, then we still need to understand what 'scientific explanation' means in the Aristotelian sense, and how 'essence' and 'cause' work within it. This analysis supports the purpose of this dissertation of contributing a more robust understanding of the historical and philosophical developments of the change in the concept of scientific explanation from Aristotle to Galileo. Furthermore, I propose that this project may also contribute a clearer framework from which to evaluate what elements of the standard model of scientific explanation (e.g. Hempel and Oppenheim, 1948; Hempel 1965; Psillos 2002) should be kept or changed in light of Brody's criticisms.

In this chapter, I pay special attention to Aristotle's use of mathematics in scientific explanation (in chapter 3, I turn to the use of mathematics by his intellectual heirs). I do this because a significant portion of the extant scholarship about the changes to scientific explanation brought about by the Scientific Revolution focuses on Galileo's purported increased use of mathematics in his scientific explanations (Kuhn, 1985; Drake, 1980; Hall, 1962; Cohen, 1960). Hence, understanding the role that mathematics plays in Aristotle's, as well as Galileo's, concept of scientific explanation will be helpful to evaluating Brody's suggestion that we should reintroduce elements present in Aristotle's concept of scientific explanation that Galileo rejected, and which rejection contemporary accounts have inherited.

2.2 Definition of and Criteria for Scientific Explanations

To understand Aristotle's concept of scientific explanation it is first necessary to understand what he means by science. Relevant to this dissertation is Aristotle's use of *epistêmê* to refer to an organized body of knowledge because this sense of *epistêmê* is often understood as 'science' or 'scientific knowledge'. Ross (1949) defends interpreting Aristotle's use of *epistêmê* to mean 'scientific knowledge': "*Posterior Analytics* present his theory of scientific knowledge. This, rather than 'knowledge' simply, is the right rendering of his word *epistêmê*; for while he would not deny that individual facts may be known, he maintains that *epistêmê* is of the universal" (p. 51). Individual facts are necessary in Aristotle's system for acquiring universals; however, individual facts are not the objects of scientific knowledge.

Smith (1995) makes the case for a translation of *epistêmê* that differs from Ross insofar as it emphasizes the scale of knowledge *epistêmê* represents:

> Aristotle's *Posterior Analytics*, especially its first book, is concerned with knowledge in a precise sense, for which he uses the word *epistêmê* (one of several Greek words for knowledge). An *epistêmê* in this technical sense is a body of knowledge about some subject, organized into a system of *proofs* or *demonstrations*: a good modern equivalent is "science," provided we drop its connotations of reliance on experimental method. (p. 47, emphasis added)

Smith points out that '*epistêmê*' refers to a body of knowledge; the organization of this precise kind of knowledge is in "proofs and demonstrations." Demonstrations, which are scientific deductions, provide the explanatory power necessary for a scientific explanation by giving the underlying causes of natural phenomena. Aristotle claims that 'understanding' requires being able to demonstrate the underlying causes of natural phenomena.

In *Posterior Analytics* I.2, Aristotle gives two conditions for scientific knowledge: "We think we understand something *simpliciter* when we think we know of the explanation because of which the object holds that it is its explanation, and also that it is not possible for it to be otherwise" (Barnes, trans., 1993, 71b9). I follow Barnes's analysis that Aristotle is providing the two necessary conditions for understanding that are also jointly sufficient, yielding the definition:

> **a** understands $X =_{def}$ **a** knows that Y is the explanation of X and
> **a** knows that X cannot be otherwise (Barnes, 1993, p. 91). [15]

[15] Not all sets of necessary and sufficient conditions are definitional in Aristotle's system.

Later I consider the question of what it means to know that *X* cannot be otherwise, but here I examine what it means for **a** to know that *Y* is the explanation of *X*.

Hankinson (1995) characterizes Aristotle's scientific explanations as follows:

> To have scientific knowledge, then, is to have explanatory understanding: not merely to "know" a fact incidentally, to be able to assent to something which is true, but to know *why* it is a fact. The proper function of science is to provide explanations, the canonical form of which is something like "Xs are F because they are G." (p. 110)

The explanations Hankinson refers to are exhibited, according to Aristotle, through demonstrations in the form of deductive syllogisms.[16] These demonstrations have explanatory power because they give the cause, or the 'why', of a given phenomenon.

Aristotle is explicit that knowledge means acquaintance with principles and causes. In *Physics* I.1 Aristotle says, "When the objects of an inquiry, in any department, have principles, causes, or elements, it is through acquaintance with these that knowledge and understanding is attained" (Hardie and Gaye, trans., 1984, 184a10). In *Metaphysics* I.1, Aristotle further explains how knowledge and understanding come from learning causes:

> But yet we think that knowledge and understanding belong to art rather than to experience, and we suppose artists to be wiser than men of experience (which implies that wisdom depends in all cases rather on knowledge); and this because the former know the cause, but the latter do not. (Ross, trans., 1984, 981a23)

Wisdom is a type of heightened knowledge or knowledge of generalities such as causes. In the *Nicomachean Ethics* VI.7, Aristotle adds that, "wisdom [*sophia*] must be intuitive

[16] Hankinson (1995) points out that the importance of syllogisms is stressed in Aristotle's writings about his scientific methodology, but this emphasis is not actually reflected in his science writings.

reason [*nous*] combined with scientific knowledge [*epistêmê*]—scientific knowledge of the highest objects which has received as it were its proper completion" (Ross, trans., 1980, 1141a18). According to Aristotle, there are four kinds of causes, that is, four kinds of answers to 'why' questions—material, efficient, formal, and final. Wisdom is about knowing the most important causes that explain why substances are the way they are. The most important cause is the *telos*; this is commonly translated as the final cause. Aristotle explains that wisdom requires knowing causes and first principles in *Metaphysics* I.1:

> all men suppose what is called wisdom to deal with the first causes and the principles of things. This is why, as has been said before, the man of experience is thought to be wiser than the possessors of any perception whatever, the artist wiser than the men of experience, the master-worker than the mechanic, and the theoretical kinds of knowledge to be more of the nature of wisdom than the productive. Clearly then wisdom is knowledge about certain causes and principles. (Ross, trans., 1984, 981b26)

In the hierarchy of knowledge, abstract, theoretical knowledge is superior to practical knowledge. The pursuit of the highest knowledge is the pursuit of the broadest explanatory principles, which are the most abstract and therefore the least pragmatically useful:

> At first he who invented any art whatever that went beyond the common perceptions of man was naturally admired by men, not only because there was something useful in the inventions, but because he was thought wise and superior to the rest. But as more arts were invented, and some were directed to the necessities of life, others to recreation, the inventors of the latter were naturally always regarded as wiser than the inventors of the former, because their branches of knowledge did not aim at utility. Hence when all such inventions were already established, the sciences which do not aim at giving pleasure or at the necessities

> of life were discovered, and first in the places where men first began to have leisure. (*Metaphysics* I.1, Ross, trans., 1984, 981b14)

According to Aristotle, the pure sciences were discovered only after all the necessary inventions and technologies had been discovered. Having attained such a high level of human comforts is, according to Aristotle, what allowed us the leisure time necessary for developing the sciences. In defense of his position on the origin of science, Aristotle claims in *Metaphysics* I.1, that, “This is why the mathematical arts were founded in Egypt; for there the priestly caste was allowed to be at leisure” (Ross, trans., 1984, 981b23). The connection between academic investigation and leisure time is apparent in our diction. The Greek word for ‘leisure’ is *schole*, which is the root of the English word ‘scholar.’

When Aristotle links leisure and discovery, it is due to his belief that all learning begins with sensory observation. A philosopher needs time to observe nature as well as time to reason out nature’s first principles, which is to say that for Aristotle scientific discovery is grounded in observation.

Observations are of particulars; *e.g.* the leaves of a particular tree at a particular date and time. However, scientific knowledge to Aristotle is not of particulars; it is of generalities, *i.e.* the universals, which are arrived at through observation of particulars. In *Posterior Analytics* I.31, Aristotle gives the example of what we would know if we could observe the Earth during eclipses from the position of standing on the Moon:

> We would perceive that it is now eclipsed but not why; for we have seen that there is no perception of universals. Nevertheless, if we observed this happening often and then hunted for the universal, we would possess a

> demonstration; for it is from many particulars that the universal becomes plain.[17] (Barnes, trans., 1993, 88a2)

The path of explanation is, however, in the opposite direction of the path of discovery. For Aristotle, the path of discovery is from what is more familiar to us, e.g. our particular observations, to what is more knowable in itself, e.g. universals. However, this does not mean that explanations are demonstrations from the universal to particular observations. Particulars are not elements of demonstrative syllogisms, even though the whole idea is for universal conclusions to *embrace* the particulars. The path of explanation is from higher-order to derivative universals and only then, contingently, to particulars. Thus, even though the universal is what *explains* the particulars, having knowledge of the demonstrations does not entail that someone know all of the particulars that are supposed to be explained by the scientific knowledge.[18] Knowing what Aristotle thinks are not the proper elements of demonstrations is a first step to understanding his concept of explanation. Next I will examine Aristotle's six conditions of a proper scientific demonstration.

In *Posterior Analytics* I.2, Aristotle lays out six criteria that are the framework for demonstrations. In this framework, demonstrations are a subset of deductions,

[17] What Aristotle means by the claim that the universal becomes clear "from many particulars" is controversial. Aristotle's term for this kind of inference is *epagôgê* and it is not clear whether Aristotle conceives of the move from particulars to universals as induction (in the classical sense), as Crombie (1953) suggests, or if *epagôgê* is too vague in Aristotle's corpus to be determined, as Smith (1995) claims, or if it is some other non-inferential process that is just a fact about how *noûs* works, as Hankinson (1995) convincingly argues. See discussion below.

[18] Aristotle makes this point in Posterior Analytics I.1: Knowing that all Fs are Gs, i.e. having the demonstration that all Fs are Gs, does not entail that someone knows of any given object X, that it is an F and hence G, even though she knows that if X is an F, then it is G.

specifically, scientific deductions. These six conditions are necessary and sufficient for a deductive syllogism to be a scientific deduction and hence a demonstration:

> . . . we say now that we do know through demonstration. By demonstration I mean a scientific deduction; and by scientific I mean one in virtue of which, by having it, we understand something. If, then, understanding is as we posited, it is necessary for demonstrative understanding in particular to depend on things which are (i) true and (ii) primitive and (iii) immediate and (iv) more familiar than and (v) prior to and (vi) explanatory of the conclusion (for in this way the principle will also be appropriate to what is being proved). For there will be deduction even without these, but there will not be demonstration; for it will not produce understanding. (Barnes, trans., 1984, 71b18-25, enumeration added)

Aristotle points out that condition (i) is obvious because it is not possible to have knowledge of that which is not true. Conditions (ii) and (iii) are less obvious; at 71b22 Aristotle lists them as ‘primitive’ (*prôtos*) and ‘immediate’ (*amesos*); however, when he lists the conditions again in the course of explaining them at 71b27, Aristotle says that demonstrations proceed from premises which are ‘primitive’ (*prôtos*) and ‘indemonstrable’ (*anapodeiktos*), which raises the question of the connection between these three terms.[19] Furthermore, because Aristotle says at 72a8 that he treats primitives and principles as the same, it is reasonable to treat Aristotle’s use of ‘primitive’, ‘immediate’, and ‘indemonstrable’ as coextensive (Barnes, 1993, p. 94). If Barnes is correct, then all three of these terms serve to identify the same premises to be suitable in scientific demonstrations.

Ross (1949) and Hankinson (1995) support the view that the terms of conditions (ii) and (iii) are coextensive. Ross (1949) asserts that what Aristotle means by the terms

[19] Some translators use ‘primary’ in place of ‘primitive’; these are simply alternative translations of *prôtos*.

‘primitive’ and ‘immediate’ is that they both require premises in demonstrations to be indemonstrable. Hankinson (1995) argues along different lines from Ross, but also supports the view that conditions (ii) and (iii) are coextensive:

> for a proposition (“all As are Bs”) to be primary is for there to be no further propositions of which it is a deductive consequence, and which serve to explain why it is the case. That means (in Aristotle’s terms) that there is no middle term C such that all As are Cs and all Cs are Bs (where A’s being C explains its being B)—and that is what it is for a proposition to be immediate. (pp. 109-10)

By showing that Aristotle’s terms ‘primary’ and ‘immediate’ do the same work in Aristotle’s definition of scientific explanation, Hankinson shows that these conditions “amount to the same thing.”

Condition (iv) requires that the premises of demonstrations be more familiar, i.e. knowable than that which is being demonstrated. Aristotle’s distinction is between that which is more knowable to us in the sense of being more apparent to us versus that which is more knowable in itself. Aristotle says that in the search for scientific knowledge we begin with what is more familiar or apparent to us, but less knowable in itself, and we move from there to what is less well known or obvious to us, but what is most knowable in itself (*Posterior Analytics* I.2, 71b33ff; *Metaphysics* VII.3, 1029b3-12). The expression “what is most knowable in itself” refers to universals, the higher-order generalizations, which have the greatest epistemic warrant. However, knowledge of universals is more remote to us because we cannot experience universals as such, only particulars (*Posterior Analytics* I.31, 87b28-33). Even though the content of our observations and experiences may seem more epistemically certain per se, Aristotle argues that this kind of knowledge cannot be scientific knowledge.

In addition to the requirement of condition (iv) that premises be of higher degrees of epistemic warrant than the conclusions, Aristotle may also be making a further, psychological requirement of the audience of demonstrations. In *Posterior Analytics* I.2. Aristotle says:

> Anyone who is going to possess understanding through a demonstration must not only get to know the principles better and be better convinced of them than he is of what is being proved: in addition, there must be no other item more convincing to him or more familiar among the opposites of the principles from which a deduction of the contrary error may proceed—given that anyone who understands anything *simpliciter* must be incapable of being persuaded to change his mind. (Barnes, trans., 1993, 72a39-72b3)

Aristotle could be understood to be requiring that audiences also be more convinced of the premises of demonstrations in order to be convinced of the conclusions. This is a difficult requirement because it is not clear how we move from being most convinced of that which is more familiar to us, such as the particulars that we observe, to becoming more convinced of the principles which have greater epistemic warrant, but which are more removed from our experience.

Conditions (v) and (vi) require that demonstrations proceed from premises that are prior to and explanatory of what is being demonstrated. Although in different places he discusses different senses of priority, by ‘prior’ here Aristotle means that the premises must be prior to the conclusions in the order of knowledge. *A* is prior in knowledge to *B* in the case that in order to know *B* we must know *A*, but having knowledge of *A* does not require having knowledge of *B* (Barnes, 1993). Hankinson (1995) links the conditions of priority and explanation even more closely: "some property *F* is prior to *G* in this sense just in case something's being *G* is explained by its being *F*" (p.110). Hence, demonstrations must proceed from premises that are explanatory of the conclusion because, in Aristotle's system, one cannot have scientific knowledge of *P* unless one knows what explains *P*.

Aristotle claims that there can be a deduction without these six conditions being satisfied however, there cannot be a demonstration of scientific knowledge because without satisfying the six conditions, there cannot be a scientific explanation. In *Posterior Analytics* II.16, Aristotle illustrates this point with the phenomenon of deciduousness. Keep in mind that a deduction that is also a demonstration and hence a scientific explanation is one where the middle term is properly explanatory of the explanandum. At 98b6 Aristotle gives the following demonstration:

(A) All broad-leaved trees are deciduous
All Vines are broad-leaved
thus, All Vines are deciduous.

Aristotle claims that deduction A is a demonstration, and hence a scientific explanation, because it answers a 'why' question: Why are all vines deciduous? Aristotle's answer is that vines are deciduous because they are broad-leaved and broad-leaved trees are deciduous. The middle term 'broad-leaved' explains why 'deciduous' holds of 'vines'. This means that Aristotle believes that 'broad-leaved' must give at least one of the "four causes". In this case, the fact that vines are broad-leaved is the formal cause of vines being deciduous because it is the form of broad leaves that facilitates their activity of shedding. Aristotle contrasts deduction A with deduction B, which uses the same terms rearranged: vines; deciduous, and broad-leaved, but which deduction Aristotle argues is not a proper explanation.

(B) All deciduous trees are broad-leaved
All Vines are deciduous
thus, All Vines are broad-leaved.

This is a deduction that proves the *fact* that vines are broad-leaved, but it is not a demonstration of scientific knowledge according to Aristotle because it does not explain the explanandum; i.e. deduction B does not explain *why* vines are broad-leaved. In other words, deduction B does not give one of the four causes. Aristotle further clarifies the distinction between deductions that prove a fact versus deductions that are demonstrations of scientific knowledge by showing that one can determine which of the possible premises produced from the same terms in a syllogism is explanatory and hence prior in the order of knowledge. Presumably, trees are not broad-leaved because they are deciduous; instead, they are deciduous because they are broad-leaved. Thus, the fact that vines are broad-leaved can be deduced from knowing that they are deciduous but not why they are broad-leaved. On the other hand, the explanation for why vines are deciduous can be deduced from the knowledge that all broad-leaved trees are deciduous (and that vines are broad-leaved). This also illustrates what Aristotle means by 'prior' in the order of knowledge (condition v above).

Hankinson (1995: 112) points out that deduction A is not really fully explanatory either, because presumably there is a further explanation as to why broad-leaved trees are deciduous. In *Posterior Analytics* II.16-17, Aristotle gives another example of a deduction concerning deciduousness that gives an explanation:

(C) All sap-coagulators are deciduous
All broad-leaved trees are sap-coagulators
thus, All broad-leaved trees are deciduous.

Like deduction A, deduction C is also a demonstration and hence a scientific explanation, according to Aristotle, because it answers a 'why' question: Why are broad-leaved trees deciduous? Aristotle's answer is that broad-leaved trees are deciduous because they are sap-coagulators. If sap coagulation explains why broad-leaved trees are deciduous and broad-leaved trees being deciduous explains why vines are deciduous, then it would seem that sap coagulation causing deciduousness is prior in the order of knowledge to the knowledge that all broad-leaved trees are deciduous, and hence more explanatory according to Aristotle. If the proposition that all sap-coagulators are deciduous is more explanatory of why vines are deciduous than the proposition that all broad-leaved trees are deciduous, then Aristotle's example (deduction A) does not meet his own criteria for a full scientific explanation. It looks like Aristotle's conditions for a scientific explanation may be difficult to implement because, although we can make reasonable guesses about when a deduction is answering a 'why' question, it remains problematic, or at least difficult, to know if a particular deduction marks the end of the chain of deductions.

There are at least two possible ways of addressing the apparent problem of whether Aristotle's example deduction A, given the existence of deduction C, meets his own conditions for a demonstration and hence scientific knowledge. First, if deductions A and C answer different 'why' questions, that is, if their explanatory power comes from identifying different causes from among the four causes, then there would not be the apparent problem of having multiple explanations for the same phenomenon in the same context. Deduction A gives the formal cause of vines being deciduous: they are broad-leaved. Aristotle spends less time discussing the example deduction C and it is less clear which of the four causes it gives. In one sense deduction C is identifying a material cause because sap is the material in leaf stems that freezes and breaks. On the other hand, deduction C might give the efficient cause of deciduousness because leaf falling occurs as a result of the event of freezing, or freezing and breaking.

The second possible answer to the question of what effect deduction C has on whether deduction A is a full scientific explanation, according to Aristotle, is that deduction A is not fully explanatory. Although Aristotle proposes deduction A as an example of a scientific explanation, if deduction C does explain deciduousness further (i.e. rely on knowledge prior to the knowledge necessary for deduction A, then once we are aware of deduction C, we must retract the claim that deduction A satisfies Aristotle's conditions.[20]

A partial remedy for the difficulty of satisfying the conditions of scientific explanations in the *Posterior Analytics* may be found in *Topics* I.1, where Aristotle

[20] There may be a third possibility. In Posterior Analytics II.17 Aristotle asks, "What is shedding leaves? – The solidifying of the sap at the connection of the seed" (Barnes, trans., 1993, 99a26). Hence, while in one sense deduction C seems to be a demonstration about deciduousness that relies on a universal prior in the order of knowledge, there is another sense in which deduction C, by supplying the definition for the key term "deciduousness" may be thought of as relying on a universal that is neither prior nor posterior to the knowledge necessary for deduction A.

claims, “It is a demonstration, when the premises from which the deduction starts are true and primitive, or are such that our knowledge of them has originally come through premises which are primitive and true” (Pickard-Cambridge, trans., 1984, 100a27). Thus, in the *Topics*, Aristotle is clearer that every demonstration need not come from a science’s first principles directly, as long as the principles that are used in the premises of the demonstration are the explanatory first principles of the phenomena being explained within a particular science. It is some evidence, but perhaps not much, for this second interpretation that Aristotle gives as an example of a demonstration deduction A, above.

Elucidating Aristotle’s discussion of his conditions for scientific explanations is a first step, to further understand Aristotle’s concept of scientific explanation it will be helpful to examine some of Aristotle’s actual scientific explanations. Next I turn to examining two cases from Aristotle’s science writings in order to further understand his methodology and to see how closely he applies that methodology to his own investigations, which will give some insight into the potential difficulties of Aristotle’s theory.

2.3 Two Case Studies: Violent Motion and the Rainbow

Violent Motion

The case study of violent motion illustrates Aristotle’s concept of scientific explanation through examining Aristotle’s views of locomotion—natural and unnatural. Aristotle says in *Physics* VII.1 that “Everything that is in motion must be moved by something” (Hardie and Gaye, trans., 1984, 241b34). Aristotle claims that every object in motion either has a source of motion within itself, as natural bodies do, or is moved by something else. Self-movers can stay in motion as long as they have a principle of motion within them and are not impeded, but non-self-movers must necessarily stop moving when the thing that is moving them stops moving (*Physics* VIII.4, 255b12).

Aristotle's distinction between self-movers and non-self-movers does not divide the world into two distinct groups: objects may be self-movers in one direction or one respect, but non-self-movers in another. The four terrestrial elements of earth, air, fire, and water offer simple examples of this in Aristotle's system. For example, when fire moves upward, it is because it is a self-mover; it has the principle of moving upward and actualizes it. Upward motion is natural for fire and so will occur whenever not impeded from doing so by an external object or agent (*Physics* VIII.4, 256a2). However, fire is a non-self-mover in the downward direction so if fire is made to move downward, it will stop moving downward when the thing that is moving it downward stops doing so. A more common example of non-self-movement is that any heavy object, such as a ball or stone, being projected upward contrary to its natural motion, which is down.

The way Aristotle presents his ideas about non-self-movers could be taken as an empirical claim that non-self-moving objects always stop moving when their movers stop moving them. To understand this claim, we would have to be able to distinguish between self and non-self-movers, and when a given body stops moving, we would have to be able to determine whether it was because an external mover had stopped moving it or rather because the body was a self-mover that was being impeded by an external body. Being able to distinguish these traits and causes is what would allow someone to make the observations necessary to come to Aristotle's conclusion about the causes of motion in bodies.

However, the extreme difficulty of making these kinds of empirical observations suggests that Aristotle came by another route to his conclusion that everything either moves itself or is moved by something else. Aristotle argues that any object that is in motion that is not moving itself must be being moved by something else. Aristotle's reasoning is that if a body does not move itself and nothing else moves it, then it would not be in motion. However, this line of reasoning is based on the assumption, either explicit or perhaps implicitly made as a part of one's worldview, that there is necessarily a cause to the motion of a body because the default state of bodies is rest. If there were one or some bodies that were in motion by nature, Aristotle's assumption that rest does not need explaining but motion does would not be justified. Aristotle's assumption may appear to be an empirically grounded one; however, it is no easier to empirically test the hypothesis that rest is primary than it is to test the hypothesis that motion is primary. It would be a mistake to assume that whatever seems more intuitive is thereby empirically based. We have intuitions based on false understanding of the physical world and incorrectly interpret physical phenomena with great ease. The great difficulty Aristotle has explaining why heavy objects continue to move unnaturally after they have left the thrower's hand reveals the problematic nature of Aristotle's assumption.

To further shed light on Aristotle's concept of scientific explanation it is helpful to examine how Aristotle uses the idea that everything that moves is either moved by itself or by something else as a fundamental principle upon which other demonstrations can be based. For example, by using Aristotle's definition of first principles we can evaluate whether his idea of the causes of motion is indemonstrable, or if instead, perhaps, there is another more primitive principle of Aristotle's theory of motion (e.g. the Prime Mover—that which moves others without being moved itself). Aristotle's theory of motion addresses the question of the origin and role of the Prime Mover, which is particularly useful for highlighting some of Aristotle's trouble in applying his own scientific method.

Understanding the role of the Prime Mover is critical because if it is a first principle that everything moved is moved by something else, then Aristotle's *reductio* in *Physics* VII.1 is valid. Aristotle argues that an absurdity results from assuming that there is not a prime mover because in that case there would be an infinite regress of bodies being moved by other bodies (242b15). This argument by itself does not yield a single prime mover, but it does produce at least one and allows for any number of unmoved movers. However, this argument would be different if Aristotle were first committed to the existence of the Prime Mover and only secondarily asserted that everything moved is moved by something in order to justify his having posited the existence of the Prime Mover, because then the Prime Mover would be a straightforward logical necessity.[21] If the theory were that all motion is caused by an external mover, then the Prime Mover would be a logical necessity in order to prevent an infinite regress. However, once Aristotle allows for self-movers, the picture becomes less clear. For instance, it is less

[21] Sorabji (1988) argues that Aristotle might be committed to the Prime Mover before he is committed to his principle of the causes of motion. This alternative view of the role of the Prime Mover is discussed below.

clear why a Prime Mover is needed if every natural object is a self-mover. This might support the idea that Aristotle is first committed to the existence of the Prime Mover and then to his theory of motion secondly.

Another possibility that might suggest that the Prime Mover serves a logical necessity instead of being a primary commitment of Aristotle's can be seen in Aristotle's definition of motion in *Physics* III.1 as the *actuality of potentiality as such* (201a11). Within this definition, motion means that something with the potential to move is actualizing that potential. Since actuality must logically but not temporally precede potentiality, all things that move have potentiality, and so there must be something that is purely actual at which they aim or nothing could ever move. Hence, the Prime Mover is pure actuality.

Aristotle encounters a problem to his theory of motion when he considers projectile motion. Again, Aristotle's view is that objects that move themselves (i.e. self-movers) are natural objects and can only move themselves according to their nature. In *Nicomachean Ethics* II.1, Aristotle says that whatever is by nature cannot be habituated against its nature. He uses an example of a stone. If one were to throw the stone upward (contrary to its natural motion) 10,000 times, the stone would never move by its own impetus in any direction but downward. The fact that self-movers can only move themselves according to their nature creates the following problem: Aristotle cannot use the explanation that the javelin is a self-mover to explain why the javelin continues to move horizontally or upward (both are contrary to its nature) after the javelin has left the hand of the Olympian. Although the javelin is still in motion after leaving the hand of the Olympian, it is always slowing down along the component of unnatural motion.

In *Physics* V.6, Aristotle tries to address this problem by saying, "But what is coming to a stop moves ever faster, while that which is moving unnaturally moves ever slower" (Hardie and Gaye, trans., 1984, 230b21). The phrase "what is coming to a stop" refers to natural bodies moving by locomotion towards their natural places, such as earthen objects falling toward the center of the universe. For example, heavy objects accelerate as they move downward, but when thrown upward they continually decelerate until they stop moving unnaturally, then they accelerate continually in their natural direction until they are impeded by something keeping them from moving lower, or until they arrive at their natural place. [22] Aristotle's explanation for why heavy objects decelerate as they move upward is that this kind of motion for these kinds of objects is unnatural. But, given that the motion is unnatural, the question arises of why objects

[22] It is less clear what Aristotle thinks about heavy objects moving horizontally. Presumably horizontal here means parallel to the ideal earth's surface. One possibility is that horizontal motion is not actively unnatural for a heavy object—in other words, since horizontal motion is not exactly contrary to downward motion, it is neutral with respect to heavy bodies. Another possibility is that Aristotle thinks that any motion other than an object's natural motion is unnatural motion. In this case, horizontal motion as well as upward motion Aristotle would consider unnatural motion. In *De Caelo* I.2. Aristotle says, "By constraint, of course, it may be brought to move with the motion of something else different from itself, but it cannot so move naturally, since there is one sort of movement natural to each of the simple bodies. Again, if the unnatural movement is the contrary of the natural and a thing can have no more than one contrary, it will follow that circular movement, being a simple motion, must be unnatural, if it is not natural, to the body moved. If then the body whose movement is circular is fire or some other element, its natural motion must be the contrary of the circular motion. But a single thing has a single contrary; and upward and downward motion are the contraries of one another" (Stocks, trans., 1984, 269a7-13). Since Aristotle knows the earth is spherical, he might accept that horizontal motion is circular motion and is thereby unnatural for heavy bodies. However, there is no reason to think that Aristotle viewed horizontal motion this way, so it is just as likely that Aristotle regards horizontal motion as neutral to heavy bodies as it is that he thinks horizontal motion is unnatural. Although this is controversial, Aristotle appears to occasionally use 'unnatural' to mean simply 'not natural' for the body in question' but not necessarily *contrary* to its nature: cf. *De Caelo* III.2, 300a20-7; Simplicius in his commentary makes use of the distinction on Aristotle's behalf – see his commentary on *Cael*. I.2 (Hankinson, personal communication, 2009).

continue moving contrary to nature at all when they are no longer being propelled by an external mover.

In *Physics* IV.8, Aristotle attempts to address how objects can move contrary to nature when he argues that any body in motion must be moving through some medium, (i.e. there cannot be a separately existing void). Aristotle says that all media resist bodies to some extent (Physics, IV.8). Aristotle claims that the speed with which a body travels is proportional to the ratio between the motive force or impulse and the weight or thickness of the medium (215b1). Aristotle further argues that one of the impossibilities that would result if there were a void is that a body unimpeded would continue moving forever. "Further, no one could say why a thing once set in motion [in a void] should stop anywhere; for why should it stop *here* rather than *here*? So that a thing will either be at rest or must be moved *ad infinitum*, unless something more powerful gets in its way" (Hardie and Gaye, trans., 1984, 215a19-21).[23]

Aristotle offers several arguments for the impossibility of void. One such argument claims that motion is impossible in a void because, since a void is unchanging and is everywhere the same, objects in that void could not change with respect to the void—changing with respect to a frame of reference is what motion is—hence no motion in a void (214b30). Another argument for the impossibility of void says that if there were a void, then motion in the void would necessarily be instantaneous because there would be zero resistance against the motion (215b23). However, the idea of instantaneous

[23] It is historically interesting that Aristotle seems to be arguing from something like the impossibility of inertia because it is the concept of inertia developed in the 17th century, as codified by Newton, that fully resolves the javelin problem.

motion is absurd; Aristotle calls it an impossibility, thus, by *modus tollens*, there cannot be void. So we see that Aristotle's understanding of motion requires that bodies can only move while a motive force is acting, and motion is only possible in the presence of a resisting medium.

Returning to the example of the javelin, in *Physics* IV. 8, Aristotle sets up a dichotomy between what he sees as the two possible explanations for the unnatural movement of the javelin: "Projectiles in fact continue to move when that which propelled them is no longer in contact with them, either by virtue of mutual replacement, or because the air propelled behind them propels them with a movement quicker than their natural movement to their own place" (215a14). "Mutual replacement" refers to the idea of antiperistasis.[24] The dynamic sense of antiperistasis that Aristotle is concerned with here is the idea that air being pushed out of the way by a projectile rushes to fill the space behind the projectile and in doing so pushes the projectile.

The second possible explanation that Aristotle considers is that the air is briefly endowed with the ability to impel the projectile by the same impetus that initially pushed the projectile (*Physics*, VIII.10, 267a5). Aristotle draws an analogy to how magnets give magnetic properties to metal objects (*Physics*, VIII.10, 267a2). A piece of metal touching a magnet will act as a magnet to a second piece of metal as long as the first piece of metal is touching the magnet. The analogy falls short, however, if we consider that the magnet is constantly acting on the first magnetized object, which is attracting the

[24] There are two distinct notions of antiperistasis: One sense is merely meant to explain how motion is possible in a plenum, but it does not give a dynamic cause of motion. The second sense, which Aristotle is concerned with here, is meant to give a dynamical explanation of unnatural motion. The idea here of the latter is that the medium actually imparts impetus to the projectile.

second piece of metal. The analogy falls short because, in the case of the magnet chain, the first magnet is always working through whatever it is touching. This is not the case with the javelin. Once the Olympian has released the javelin, the Olympian (or Olympian's arm) can no longer be doing any work on the javelin in Aristotle's system. A preferable analogy might be one where the first mover imparts the ability to move for a short time after the first mover has stopped moving. Perhaps an object fixed to a loaded spring is a closer analogy.

In his demonstration, Aristotle treats antiperistasis and the air becoming a mover as the only two possible resolutions of the problem of unnatural motion. If this were an exhaustive list as Aristotle implies, Aristotle would only need to show that one possibility is false in order to demonstrate the veracity of the other possible explanation. This kind of disjunctive syllogism is often used by Aristotle.[25] However, if another possibility exists, then Aristotle's argument fails because he fails to account for all possibilities, i.e. the disjunction will not be exhaustive. For instance, another possibility is that, rather than the Olympian imparting the quality of being a mover to the air behind the javelin, the Olympian imparts the property of being a mover directly to the javelin, which then becomes a self-mover for a time. Since the javelin is by nature a self-mover downward, the Olympian would briefly impart the ability to be an upward self-mover to the javelin. This possible explanation for the javelin continuing to move unnaturally after leaving the hand of the Olympian maintains the same basic form of Aristotle's solution (that the air

[25] For example see the discussion below of Aristotle's explanation for the cause of thunder in *Meteorology* II.9, where Aristotle argues for his theory by eliminating what he assumes are the only two possible alternatives.

behind the projectile becomes a mover): both explanations consist of transference of self -motive capacity from the Olympian to something else. This possibility that Aristotle does not consider would seem to be a neater resolution than Aristotle's because it is more direct, giving the self-moving ability directly to the javelin instead of to the air, a third thing that has to keep moving the javelin. Another advantage of this possibility not considered by Aristotle is that it would not be susceptible to Philoponus' counterargument.[26] Philoponus' counterargument to Aristotle rests on the common experience of the inability of people to push air fast enough to generate the kinds of force necessary to propel a javelin or other projectiles at great speed.

John Buridan (1300-1358 C.E.) raises the question of why Aristotle did not consider the apparent problem that under his system, air both resists and propels bodies: air resists insofar as it is dense, as all media resist motion, and propels insofar as the property of being a mover of javelins is transferred to it by the Olympian's arm (Dugas, 1998). The implication of this is that when the air becomes a self-mover of the javelin, it must push the javelin against itself, i.e. more air. Aristotle may begin to address this concern in *De Caelo* III.2, where he explains how it is that air helps move things both up and down. "For air is both light and heavy, and thus *qua* light produces upward motion, being propelled and set in motion by the force, and *qua* heavy produces a downward motion" (Stocks, trans., 1984, 310b23). In his discussion about how the Olympian imparts to the air the ability to continue to move the javelin unnaturally, Aristotle does

[26] John Philoponus (c. 490-570) commentated on Aristotle's *Physics* and articulated impetus theory, which claims that the thrower temporarily imparts the ability to be a self-mover to the javelin. Impetus theory was a precursor to the 17th century theory of inertia (Drake, 1970).

not explain just what it is about air that gives it the potential to become a mover of javelins. Aristotle speaks in general terms about the problem of unnatural motion, so it seems very likely that it is not a property of air as such that allows it to become a mover, but that air is a medium through which objects move. Water must also work the same way that air does. Air helps things move up and down because it is heavy and light.

The root of the problem Buridan points out may also be the solution to another apparent problem: if the air becomes a mover of the javelin, why does the air stop moving the javelin, i.e. why does the javelin slow down? If Buridan is right that in Aristotle's system the air is ultimately pushing against itself, then perhaps this is why the javelin slows down along the unnatural direction of motion. The air is losing its ability to move the javelin because it is working against itself.

The Rainbow

Evaluating Aristotle's treatment of meteorological phenomena provides additional insight into his concept of scientific demonstration. Aristotle says that each of the phenomena—halos, rainbows, mock suns, and rods—is a reflection. Although these phenomena are all reflections, they exhibit differences which Aristotle accounts for through the different natures of different reflecting surfaces and the different bodies being reflected. In *Meteorology*, III.2, Aristotle claims that:

> We must accept from the theory of optics the fact that sight is reflected from air and any object with a smooth surface just as it is from water; also that in some mirrors the shapes of things are reflected, in others only their colours. Of the latter kind are those mirrors which are so small as to be indivisible for sense. (Webster, trans., 1984, 372a29)

This quotation introduces Aristotle's first premise: vision is reflected from smooth surfaces such as air and water.[27] This is an example of how Aristotle relies on facts from other sciences as principles in later investigations; here optics is the prior science. So, from optics we accept that smoothness is responsible for reflection. However, it is not clear that optics gives us mirrors "indivisible for sense." If Aristotle could prove the existence of tiny mirrors, then his argument would be sounder. "Indivisible for sense" means something like undetectable by the senses—invisible. The idea is that the mirrors are so small as not to present a surface which can be registered as being divisible by sight (if I see an ordinary mirror, I see its left side and its right side). The existence of an invisible thing is not easily proven directly. So it seems that Aristotle has derived or inferred the existence of invisible mirrors from the phenomena he is attempting to explain.[28] Aristotle might be on firmer ground if he were to begin arguing for the existence of invisible mirrors based on the phenomena of rainbows, halos, etc. than he is when arguing for the existence of these phenomena based on the postulated fact of invisible mirrors. We can hypothesize that Aristotle came to posit invisible mirrors by reasoning from the phenomena using something like evidence to the best or most

[27] It is helpful to note that Aristotle's theory of vision is not based on the idea that light, such as sunlight, is reflected off objects to the observer. Instead, Aristotle has some other idea of what is transmitted between the object and the observer that gives one the mental images of objects. See *De Anima* II.6 and III.1.

[28] The form of the argument here is the following: We observe some phenomenon F; we reason that F could only be the case if nature is G; hence, nature must be G. This kind of argument can introduce error especially when there is no independent test that can corroborate nature's being G. We will see this kind of error elsewhere in Aristotle, Ptolemy, and the Aristotelians of Galileo's time. Moving away from this kind of reasoning may be among Galileo's greatest influences on the development of modern science.

reasonable explanation.[29] Then in the *Meteorology*, we are given the demonstration of the phenomena, which proceeds in the opposite direction from the path of discovery. For instance, Aristotle gives a mathematical demonstration of why halos are circles or segments of circles in *Meteorology* III.3 (373a2-a17) and a demonstration of why rainbows can never be greater than semicircles in III.5. In these demonstrations nature is assumed to follow geometrical space; in other words, geometry is a prior science to the physical sciences.

In *Meteorology*, III.2, Aristotle argues:

> It is impossible that the shape of a thing should be reflected in them; for if it is the mirror will seem divisible—for every shape is at once a shape and divisible. But since something must be reflected in them and shape cannot be, it remains that colour alone should be reflected. (Webster, trans., 1984, 372b1)

Here we are given the second premise of Aristotle's argument: some mirrors, those indivisible for sense, reflect only color and not shape. Aristotle concludes from the fact that they are mirrors and by definition must reflect something, but cannot reflect shape that they reflect color. But Aristotle cannot intend this to be his argument because this line of reasoning would violate Aristotle's requirement that explanations proceed from broader explanatory principles than the conclusion. The indivisible mirrors do not reflect color *because* they must reflect something and cannot reflect shape. The indivisible mirrors only reflect shape *because* they cannot reflect both color and shape the way divisible mirrors do. Aristotle reasons from the geometrical fact that shapes are divisible

[29] This process is very closely akin to *analysis*, which will be discussed at length below.

to the conclusion that if a shape is reflected then the reflecting surface must also be as divisible.

In *Meteorology,* III.2, Aristotle adds another component of reflections:

> The colour of a bright object sometimes appears bright in the reflection, but it sometimes, either owing to the admixture of the colour of the mirror or to weakness of sight, gives rise to the appearance of another colour. (Webster, trans., 1984, 372b6)

Brightness now seems to be a third property that is reflected; it is reflected along with color. Furthermore, Aristotle seems to be treating brightness as if it is itself another color, which would serve to explain why he does not treat it as a distinct property. If it were just the intensity of the color that was reflected (that is, if the color of the incidence ray were always the same as the color of the reflected ray), it would not seem to be a third reflected property. However, Aristotle claims that even though the brightness is reflected, sometimes the color of a bright object may be reflected as a different color. Aristotle attempts to account for the change in appearance of colors as being dependent on the amount of vapor causing the reflection; for example, "white color on a black surface or seen through a black medium gives red" (374b10).[30]

> Since each of the mirrors is so small as to be invisible and what we see is the continuous magnitude made up of them all, the reflection necessarily gives us a continuous magnitude made up of one colour, each of the mirrors contributing the same colour to the whole. (Webster, trans., 1984, 373b25)

[30] Presumably Aristotle was also familiar with the phenomena of colored mirrors; however, he does not suggest that colored vapor is what causes the phenomena being considered here.

This gives us the conclusion to Aristotle's argument: the rainbow is a reflection of sunlight in indivisible mirrors of water vapor or mist, each reflecting only a particular color, but the whole of which produces the rainbow's arch and colors. This explanation satisfies Aristotle's requirement that there be no obvious impossibilities when explaining phenomena that are difficult to observe, a requirement he cites in *Meteorology* I.7: "We consider a satisfactory explanation of phenomena inaccessible to observation to have been given when our account of them is free from impossibilities" (Webster, trans., 1984, 344a5). However, Aristotle's explanation of the rainbow does not exactly proceed by rigorous deductions and demonstrations as he describes in the *Posterior Analytics.*

Aristotle briefly addresses the colors of the rainbow. He says there are three: red, green, and violet (374b30). He adds that yellow can appear between the red and the green but this is just due to the contrast between red and green. The reason the colors are in the order they are is, according to Aristotle, because of the impact the distance has on our sight, but this is not rigorously explained. In *Meteorology* III.4 Aristotle appears to be suggesting that distance influences visions ability to detect color because colors that are farther away are fainter and cannot as easily penetrate brighter colors that are nearer to the observer.

In his discussion of the halo, Aristotle further explains how vapor reflects differently to produce different phenomena.

> Sight is reflected in this way when air and vapour are condensed into a cloud and the condensed matter is uniform and consists of small parts. (Webster, trans., 1984, 372a16)

The more mist the darker the halo; this is why halos around the Moon are more common than halos around the sun, namely, because the Sun evaporates more of the vapor near it because of its greater heat. Since Aristotle does not think any of the four terrestrial elements reside in the vicinity of the heavenly bodies, the actual location of halos must be between the heavenly bodies and the observers on the ground. However, the mist or vapors are close enough to the heavenly bodies to be affected by the heat of heavenly bodies.

One potential problem with Aristotle's idea about halos is that, if the only factor contributing to the amount of mist around a heavenly body were how little heat it has, then we might expect even more mist, and thereby even darker halos around the stars than the Moon. However, Aristotle says about stars that "the condensation they imply is so insignificant as to be barren" (373a27). Apparently, heavenly bodies dissipate condensation both according to size and heat. Presumably distance is also a factor, because halos cannot be proximate to heavenly bodies. Aristotle may have a tacit idea of heat dissipation over distances. It is not surprising that Aristotle would assume correlations among size, brightness, and heat. This would capture why the stars have insignificant heat: compared to our observations of the Moon, they are of insignificant relative size. Furthermore, condensation cannot just be due to relative distance either since the Sun is further away.[31] This exemplifies both Aristotle's reliance with

[31] This case exemplifies the critical role that one's theoretical framework plays in understanding observations. Aristotle's demonstration of the effects that the heat of heavenly bodies has on meteorological phenomena such as rainbows and halos relies heavily on his beliefs about the composition of heavenly bodies, their distances and sizes, and heats, all of which are qualities that are difficult if not impossible to observe. The relationship between theoretical framework and observation is discussed in chapter 4.

observation and the problem with relying on observation. Relying solely on our observations is not perfect, however, because to the naked eye, the Sun and Moon appear to have equal diameters, although they do not give off the same amount of heat. Hence there must be more factors in determining the heat of celestial bodies.

Aristotle argues that the reflecting body is condensed air and vapor. These kinds of mirrors indivisible to sense have a rough composition and so they reflect only color. On the other hand, in *Meteorology* III.4, in his description of the reflective properties of smooth things, Aristotle says that air itself can be reflective, as in the case of the man whose sight is so weak that he always sees his own shape in front of him.

> Air must be condensed if it is to act as a mirror, though it often gives a reflection even uncondensed when the sight is weak. Such was the case of a man whose sight was faint and indistinct. He always saw an image in front of him and facing him as he walked. This was because his sight was reflected back to him. Its morbid condition made it so weak and delicate that the air close by acted as a mirror, just as distant and condensed air normally does, and his sight could not push it back. (Webster, trans., 1984, 373a35-b10)

Aristotle implies here that vision literally penetrates air, so the vision of healthy people, cuts through the air near them and nothing is reflected back.[32] However, for the very weak-sighted man, even the thinnest air acted partly as a wall upon which his vision would bounce back at him. Since this man is seeing a shape, these are not the same mirrors that cause the atmospheric phenomena Aristotle is talking about, which reflect

[32] Aristotle appears to be relying on some sort of visual ray theory here, but it is not clear that this is consistent with his more developed account of sight in *De Anima* II.6 and III.1 because there he claims that vision is not a matter of the eyes emitting something that is reflected back to them.

only color and not shape.[33]

Aristotle continues his halo discussion by stating that halos are reflections of light from the mist that forms around the heavenly bodies, or more accurately around the image we see of a heavenly body far removed from the body itself. That we apparently see halos around heavenly bodies explains why halos are circular and not seen opposite the Sun the way rainbows are. Aristotle's demonstration of why the halo is circular is mathematical in form:

> Since the reflection takes place in the same way from every point the result is necessarily a circle or a segment of a circle; for if the lines start from the same point and end at the same point and are equal, the points where they form an angle will always lie on a circle. (Webster, trans., 1984, 373a2)

I illustrate Aristotle's conception of the halo in Figure 2.1 below.

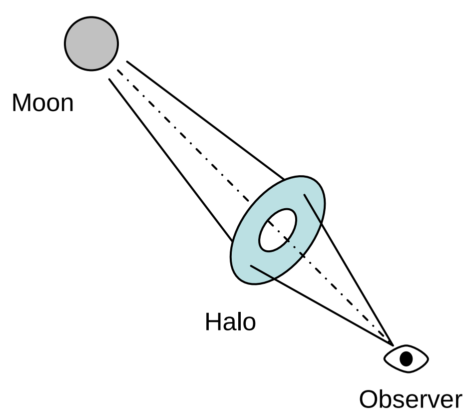

Figure 2.1
The dashed line represents light that travels straight from the Moon to the Observer. The Moon's heat evaporates the mist directly in the path of the dashed line, giving the halo its washer shape. The solid lines represent oblique light from the Moon that is reflected by Mist back to the Observer.

[33] Likewise, when calm, water reflects both color and shape, as it does in a pond. When the water surface is calm, each point of water is even with or, in a sense, continuous with, every other point. Only when water is rough or the medium is a combination of water and air, as it is in mist, are the conditions able to produce the right type of reflective objects for rainbows and halos.

Aristotle's explanation for the circularity of halos hinges on his being able to apply the geometrical definition or construction of a circle to physical observations. Insofar as any halo is circular, then, it will have all the geometrical properties of circles. Thus, we will be able to construct demonstrations about its properties (conditional upon how closely it approximates a circle).

Aristotle also uses observations about the dispersal effect that wind has on halos as evidence for the composition of halos and the other reflective phenomena. Aristotle reports that when the wind comes from the direction of the observer to the halo, the wind is felt before the halo is dispersed; when the halo disperses first, the observer is sure to feel a wind coming from the direction of the halo soon. Aristotle argues that the connection between wind and halos is strong enough to enable an observer to predict the rain based on what happens with a halo:

> Hence it is a sign of rain, but if it fades away, of fine weather, if it is broken up, of wind. For if it does not fade away and is not broken up but is allowed to attain its normal state, it is naturally a sign of rain since it shows that a process of condensation is proceeding which must, when it is carried to an end, result in rain. (Webster, trans., 1984, 372b15)

Aristotle demonstrates that halos are closer to us than they are to the heavenly bodies that, from our perspective, due to the higher wind at higher altitudes, they appear to encircle. Aristotle's reasoning is that since wind disperses halos, halos must appear nearer to the ground, where the wind is calmer. What is not clear is the order of explanation for these two phenomena: either Aristotle knows first that the wind is calmer nearer the ground and so this must be where halos are formed, or Aristotle knows first that halos appear near the ground (for instance because mist is both air and water, and since water's natural place is down, it could not be too far away), and so we know the winds are calmer closer to the ground because that is where halos are.

To envision the account that Aristotle gives about the appearance that halos encircle heavenly bodies though they are in fact much closer to us, imagine the rings of Saturn removed to a spot halfway between Saturn and the Earth but oriented such that they circumscribe the image of Saturn. This model for the geometry of a halo is consistent with Aristotle's account, but the problem with this representation of the halo is that the reflecting part of the mist would then have to be equidistant from both the observer and the object it appears to surround. Furthermore, the reflecting mist-mirrors would need to be oriented perpendicular to the Earth's surface which would work for the Moon, on Aristotle's cosmic architecture, but not for anything else. The point is that Aristotle's mathematics is suggestive of an explanation, but ad hoc, and inconsistent with Aristotle's own physical model of the heavens, which requires that the celestial bodies are much further away from Earth than twice as distant as the highest mist.[34]

The meteorological phenomena discussion provides an example of Aristotle's application of his theory of scientific demonstration. One key feature to note is the way in which, in addition to relying on observation and inference, Aristotle's demonstration relies on mathematics. Specifically, in Aristotle's demonstration of the properties of the halo the mathematical argument he applies is ad hoc because it does not apply to any of

[34] Aristotle's physics posit that the elements are arranged in a hierarchy with earth at the bottom, followed by, in equal parts, water, air, fire, and finally the ether. Mist is watery air, so it must be much closer to the surface of the Earth than the ethereal celestial bodies are to the mist.

the other similar meteorological phenomena nor even to other halo conditions (e.g. the angle of orientation to the heavenly bodies other than the Moon).

Consider Aristotle's use of mathematics in his explanations about the properties of the rainbow: Aristotle argues that the greatest arch a rainbow can be is a semicircle when the Sun is at the horizon and only less than a semicircle when the Sun is above the horizon (371b26; 375b26).[35] By demonstrating this proposition, Aristotle thinks he has shown why the rainbow cannot be greater than a semicircle. Applied to the rainbow, the given ratio is comprised of the lengths from the Sun to the rainbow and from the rainbow to the observer. As the Sun moves, this ratio remains constant and describes a circle. The circle described by this ratio is formed by a cone with the Sun at the apex. One side of the cone connects the Sun to the observer; the other side of the cone connects the Sun to the circumference of the rainbow. The first side of the cone also creates the diameter of the circle. When the Sun is at the horizon, the lower side of the cone is the same line as the horizon line, so exactly half of the circle described by the rainbow is visible. As the Sun moves, the diameter of the circle dips below the horizon line and thus the visible part of the circle described by the rainbow is less than a semicircle. When the Sun is at the meridian, no rainbow is visible.

Aristotle is right about the inverse correlation between the height of the Sun and the size of the arch of the rainbow. However, without stating it, Aristotle's demonstration of the cause of the angle measure of the rainbow tacitly assumes the law of

[35] Heath (1949) claims that this proposition, which is not in Euclid but easily derivable from *Elements* VI.3, appeared in a now-lost treatise by Apollonius. Apollonius' proposition, recorded by Eutocius, says, "Given two points in a plane and a ratio between unequal straight lines, it is possible to describe a circle in the plane such that the straight lines inflected from the given points to the circumference of the circle shall have a ratio the same as the given one" (Heath, trans., 1949, p.181).

reflection—that the angle of incidence equals the angle of reflection. This is what allows the exact inverse correlation in Aristotle's model between the height of the Sun and the size of the arch of the rainbow. Without this assumption, the demonstrated proposition above would not necessitate that the interaction between light and mist behave the way Aristotle requires.[36]

Aristotle's discussion of the rainbow also further reveals Aristotle's practice of combining elements from different sciences in the mixed sciences including, of course, mathematics. To learn about properties of the rainbow's arch, it is possible that Aristotle began by observing the properties of this particular geometrical proposition[37] and thereby inductively discovered the theorem that rainbows are never greater than semicircles and change inversely with the height of the sun. It is more likely, however, that Aristotle knew the geometrical proposition first and then applied it to his observations because he would have already been aware of the geometrical proposition (Heath, 1949).

Greater insight into Aristotle's concept of scientific explanation is gained by further examination of the role of mathematics in his scientific explanations. Evidence for this claim comes from the beginning of the *Posterior Analytics*, where Aristotle argues that scientific knowledge is exhibited through successive deductive syllogisms, which meet the criteria for demonstrations, as discussed above.

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[36] This broaches a question fundamental to scientific explanations, which Aristotle does not explicitly address. Because the law of reflection cannot be determined *a priori*, Aristotle's demonstration about the rainbow cannot have a greater level of epistemic justification than is warranted by the accuracy of the empirically determined law of reflection. By not taking into account the relative levels of justification, Aristotle introduces a source of error. This topic is discussed later in chapter 2 and in chapter 5.

[37] This refers to the proposition given, above, that enabled Aristotle to demonstrate the relationship between the angle of the Sun and the degree measure of the rainbow: "Given two points in a plane and a ratio between unequal straight lines, it is possible to describe a circle in the plane such that the straight lines inflected from the given points to the circumference of the circle shall have a ratio the same as the given one" (Heath, 1949, p. 181).

> All teaching and all learning of an intellectual kind proceed from pre-existent knowledge. This will be clear if we study all the cases: the mathematical sciences are acquired in this way, and so is each of the other arts. (Barnes, trans., 1993, 71a1,)[38]

So we see that there is an important connection between the study of mathematics and the other the sciences. Smith (1995) highlights the connection.

> Aristotle's model for a science was the mathematical disciplines of arithmetic and geometry, which in his time were already being presented as systematic series of deductions from basic first principles. (p. 47)

In some cases epistemically certain first principles can be borrowed from the mathematical sciences, but of course, the empirical sciences will still need empirical input. To better understand Aristotle's concept of scientific demonstration, the next section more closely examines Aristotle's philosophy of mathematics, in particular the way in which mathematics can inform demonstrations of scientific knowledge in Aristotle's empirical sciences.

2.4 Philosophy of Mathematics: How Mathematical Propositions Inform Demonstrations in the Empirical Sciences

The general question in this chapter is what constitutes a scientific demonstration for Aristotle. In particular, we are interested in what counts as a demonstration in the empirical sciences, as opposed to the purely mathematical sciences. Because Aristotle

[38] As the opening lines of *Posterior Analytics* this grand statement is characteristic of Aristotle's exordia. See the beginning statements of the *Physics, Metaphysics,* and *Nicomachean Ethics* among others.

holds up the mathematical sciences as a paradigm for demonstrating scientific knowledge, it is important to consider what the differences are between studying mathematics and studying nature. This will help address the question of how demonstrations of natural phenomena might need to be different from mathematical demonstrations. Although, in Aristotle's system, all sensible, and some non-sensible, objects are the combination of form and matter, the nature of this combination in mathematical objects is different from that of the objects of the empirical sciences.

> The next point to consider is how the mathematician differs from the student of nature; for natural bodies contain surfaces and volumes, lines and points, and these are the subject-matter of mathematics. (*Physics* II.2, Hardie and Gaye, trans., 1984, 193b23)

There is a sense in which the material cause of 'triangle' is 'plane figure', and in this sense the mathematician is concerned with the matter of mathematical objects and how they are formed. However, since experience implies sensation, it is apparent that we can only experience mathematical objects that are instantiated in the same matter that comprises all terrestrial objects: earth, air, fire, water. However, this kind of matter is only incidental to mathematical objects, all that matters for geometrical objects is extension; this is not the case with the objects of the empirical sciences.

Students of nature, on the other hand, are concerned with change. This is apparent, for instance, in the *Physics* where Aristotle says that the study of nature is primarily the study of change, in particular, though not exclusively, motion. Change is only possible in matter.[39] Thus, the fact that natural objects are a combination of form and matter is essential to studying them.

> How far then must the student of nature know the form or essence? Up to a point, perhaps, as the doctor must know of sinew or the smith bronze (i.e. until he understands the purpose of each); and the student of nature is concerned only with things whose forms are separable indeed, but do not exist apart from matter. … The mode of existence and essence of the separable it is the business of first philosophy to define. (Hardie and Gaye, trans., 1984, 194b10-15)

Aristotle is drawing a distinction here between the way the forms of mathematical objects on the one hand and the forms of objects in nature on the other are instantiated in matter. Aristotle says that there is a sense in which mathematical objects can be separated in thought from their physical material, i.e. earth, air, fire, water—without causing an error. The error avoided is one of leaving out something essential to an object being investigated. This is not true of natural objects, which essentially involve their particular combinations of matter, even in thought, because they necessarily involve change. The distinction is difficult to articulate because it is also true that every particular mathematical object does in fact inhere in physical matter as do natural objects. That is, any time we see a shape and call it, say, a triangle, that triangle inheres in whatever material it is made of, whether it is the steel beams of a bridge support or the chalk on a blackboard proof. One hint about the difference that Aristotle is trying to draw is apparent in our use of the expression ‘instantiated in’. It makes sense to us to talk about the same mathematical objects being *instantiated in* different matter, but it makes less

[39] This is in fact a logical requirement—matter just is what persists through change (*Physics* I.7).

sense to say that the same animal is instantiated in different matter. Although knowledge of mathematics and knowledge of natural science are both about forms (e.g. universals about triangles, circles, bears, eclipses, etc.), the difference is that it is not possible to understand the essence of a bear without including that bears are essentially in specific kinds of matter as opposed to mathematical objects, which Aristotle says are only incidentally in physical matter. It is still the case that mathematical objects essentially involve matter in the sense of extension. The difference is that even though both kinds of objects are only found in physical matter, only natural objects cannot be understood without their physical matter.

An analogy can be drawn between the definitions of different kinds of attributes and the relationships between natural objects and their physical matter versus mathematical objects and the physical matter they are instantiated in.

> This becomes plain if one tries to state in each of the two cases the definitions of the things and of their attributes. Odd and even, straight and curved, and likewise number, line, and figure, do not involve motion; not so flesh and bone and man—*these* are defined like snub nose, not like curved. (*Physics* II.2, Hardie and Gaye, trans., 1984, 193b23)

Some attributes can be defined independently of the things they inhere in; for example, curved, white, odd, and even. However, this is not the case with attributes such as snub. Aristotle points out that snub can only be defined with reference to what is snubbed, i.e. noses, such as Socrates' snub nose. This difference between these two kinds of attributes is analogous to the difference between mathematical objects and natural objects. Mathematical objects can be defined without reference to their physical matter because their definitions are independent of motion. However, objects of the empirical sciences, such as the examples Aristotle gives: flesh, bone, and man, all require reference to their specific kinds of physical matter, which are the material causes of their motions. Aristotle further illustrates this with his description of what it is to be an axe: an axe necessarily has to be able to take an edge, which only certain combinations of elements can facilitate (*Physics* II.9; *Metaphysics* VIII.4).

The forms of objects in nature involve their motion, e.g. their coming to be, locomotion, degradation, etc. This means that while the student of mathematics is primarily concerned with the forms of mathematical objects insofar as they are separable from the material they inhere in, the student of nature is concerned with the forms of objects as necessarily embodied in matter of determinate types. Next we will consider Aristotle's other uses of mathematics in the study of nature, namely how mathematical objects can be used to represent empirical objects, and how mathematical propositions can serve as axioms in demonstrations about natural objects.

Some contemporary accounts claim that mathematics does not play a significant role in Aristotle's empirical sciences (Fehér, 1982; Gaukroger, 1978; Annas, 1976; Mueller 1970). Evidence for this position includes reference to a definition for motion broadly construed, where motion is any form of change, in *Physics* III.1 as the actuality of potentiality as such (201a11). In such a definition there is no place for mathematics that could serve any explanatory role. In *Metaphysics* VIII.3 Aristotle says, "we find greater exactness where there is no magnitude, and the greatest exactness where there is no motion" (Tredennick, trans., 1935, 1078a9). This suggests that Aristotle thinks that where there is need for measurement, there is inaccuracy and that demonstrations that rely on measurements are less accurate or less explanatory than demonstrations that do not. Aristotle's claim is taken as evidence that Aristotle thinks one should eliminate the mathematical as far as possible in order to get at the essences or definitions of objects of nature, implying that nothing in those essences is mathematical as such—although it will on occasion involve loose quantitative notions ('the more and the less').[40] This view of Aristotle's empirical sciences suggests that the non-mathematical definition of motion, given above, is evidence that even if mathematics is necessary for measuring particular motions, mathematics is not essential to understanding motion and hence is not essential to understanding nature, because the science of nature is the science of motion or change (*Physics* II.1).[41]

However, the view that mathematics is only incidental to Aristotle's understanding of empirical scientific investigation fails to account for cases where fundamental mathematical properties do seem to carry explanatory power for Aristotle. We get clues of this in examples such as a discussion about the kinds of motion, found in the *Physics* and in *De Caelo*. Circular motion is the simplest, purest, most godlike and best because of the properties of circles: circles are everywhere the same and they return

[40] The view that Aristotle's empirical science investigations do not hold a significant place for mathematics will be sharply contrasted below in the discussion of the importance of quantitative measurement to Galileo's method.
[41] If this were Aristotle's view, it could be criticized from a contemporary perspective for not seeing the value in relating the definitions of the elements of the science to the function of the science. This idea is something like what Bridgman (1927; 1936) has in mind by "operationalizing" physical concepts.

on themselves without change.[42] This is significant because it suggests that mathematics can serve essential roles in Aristotle's science.

There are different ways that mathematics can enter Aristotle's explanations: one way is through appeal to qualitative mathematical properties (e.g. superiority of circular motion over straight motion in *De Caelo*, I.1); another way is by appeal to ratios. For instance, Aristotle says in *Physics* III.4, "The science of nature is concerned with magnitudes and motion and time" (Hardie and Gaye, trans., 1984, 202b30). Because Aristotle neither talks about nor uses quantitative measurements in his scientific demonstrations, "magnitudes" in the quotation above should be thought of as qualitative differences in ratios. In this sense, Aristotle is saying that the science of nature is concerned with measurement. For instance, as discussed above, in the explanation of the greatest possible arc measure of the rainbow, Aristotle uses a geometrical proposition to determine the ratio between the height of the Sun and the angle measure of the rainbow's arch.

Some further evidence of Aristotle's use of mathematics in scientific explanations may come from the pseudo-Aristotelian treatise *Mechanics*. Although Aristotle did not write the *Mechanics*, it may still serve as a very close, at least temporally, interpretation of Aristotle's views on mechanics.[43] We are also told explicitly in the *Mechanics* that mathematical truths can provide an answer to the *why* question in physical problems: "They [mechanical problems] have something in common with Mathematical and with

[42] See *Physics* IV.14; *De Caelo* I.1.
[43] It is of historical interest to note that during Galileo's time the author of the *Mechanics* was still uncontroversially thought be Aristotle.

Natural Speculations; for while Mathematics demonstrates *how* phenomena come to pass; Natural Science demonstrates *in what medium* they occur" (Forster, trans., 1984, 847a26). The heart of the *Mechanics* is to explain the various phenomena associated with the lever: "The original cause (*tês aitias tên archên*) of all such phenomena is the circle" (Forster, trans., 1984, 847b16). Properties of the circle are used to explain (*dêloô*) *how* the lever does what it does. The questions relevant to our investigation here are: What is the set of relevant mathematical objects, properties, facts and truths applicable to demonstrations about nature? What exactly is the status of these mathematical objects? And, how exactly do these mathematical objects causally explain natural phenomena?

If Aristotle wants mathematical truths to serve as the axioms in demonstrations about natural phenomena, then he must be able to show that mathematical propositions satisfy his six requirements for scientific axioms, as discussed in chapter 2.2 above. Unfortunately, in his explanation of the six requirements, Aristotle does not offer mathematical examples for all of them. He does, however, begin with one: "Now they must be true because one cannot understand what is not the case—e.g. that the diagonal is commensurate" (71b26). Aristotle probably started with the truth condition because it is the least controversial; it would be hard to doubt the criterion that demonstrations need be based on true propositions and so the mathematical example cannot illustrate anything particularly mathematical about the requirement. Nor is it controversial, that *given* things like squares, diagonals, and commensurability, it is true to say that the diagonal is incommensurate.

What is interesting about this mathematical example is revealed when we question the way in which these mathematical things are *given.* If it is true that, for instance, F holds of G, then at least one of the following is implied: (i) either this statement entails that there are such things as Fs and Gs, or (ii) this proposition entails the conditional—if there are such things as Fs and Gs, then Fs hold of Gs. In terms of mathematics the conditional would be expressed, e.g., as: if there are such things as squares and diagonals, then they are not commensurate. What follows from this is that either Aristotle needs to hold that mathematical objects exist in some way that supports their properties being used in propositions in demonstrations, or Aristotle needs to hold that conditionals can serve this purpose. If the latter, then there would be a strange conditionality to demonstrations involving math about the physical world that Aristotle does not suggest. For instance, when he demonstrates the greatest angle measure of the rainbow, Aristotle does not say that there is anything conditional about the demonstration or that the demonstration only holds if there are semicircles. In fact, it is a part of the structure of demonstrations that their axioms are *not* conditional—they cannot be otherwise. An implication of Aristotle's account of universals is that they are not merely quantified conditionals—they have 'existential import'.[44]

Lear (1982) argues that the bulk of Aristotelian scholarship has erred by giving a lower ontological status of mathematical objects than Aristotle gives them in the *Metaphysics.* Lear supposes that the reason for the misrepresentation of the status of mathematical objects comes from Aristotle's strong anti-Theory of Forms language in his

[44] This is a consequence of what Aristotle takes to be valid moods, e.g. Darapti in the 3rd figure—all As are Bs, All As are Cs, so some B is C. (*Prior Analytics* I.6)

scientific works. Lear (1982) points to the following passage from the *Metaphysics* to support his claim about the ontological status of mathematical objects in Aristotle's corpus:

> …so this is also true of geometry. If the things of which it treats are accidentally sensible although it does not treat of them qua sensible, it does not follow that the mathematical sciences treat of sensible things—nor, on the other hand, that they treat of other things which exist independently apart from these. (Ross, trans., 1984, 1077b21-25)

The implication of this passage relevant to our understanding Aristotle's concept of scientific explanation is that geometry studies objects that are *tied* to physical objects, even though it does not study them *qua* sensible. Hence, we may yet be able to use mathematics as a model for explanations in the empirical sciences because they also treat objects as *tied* to physical objects. (The connection between empirical science and physical objects is more straightforward.)

Lennox (1986) points to optics, mechanics, astronomy and harmonics as essentially involving mathematics for Aristotle. This does not mean, however, that mathematical objects inform empirical investigation for Aristotle in the same manner that they do for Galileo or for contemporary scientists. Even if mathematics are essential in the areas of natural science Lennox mentions, the mathematics might still only be used by Aristotle to help explain qualitative properties in those sciences, such as the preference for circular motion because it is more perfect than rectilinear motion. For example, the fact that in the pseudo-Aristotelian treatise *Mechanics*, the circle is said to be the essence of the lever does not obviously lend itself to applying mathematics to make further (empirical) discoveries.

Lennox (1986) is trying to show that Aristotle's concept of scientific explanation relies profoundly on mathematics.

> In the areas that most fascinated Galileo and his contemporaries—optics, mechanics, astronomy, and harmonics—Aristotle's philosophy of science insisted upon the use of geometrical and arithmetical principles. …The relevant claim of Aristotle's, which it will be my task to understand and make clear, is that there are certain sciences—optics, harmonics, mechanics, and astronomy—that involve both empirical observation and mathematical demonstration. (p. 31)

Lennox adduces five examples intended to reveal and explicate Aristotle's reliance on mathematics in demonstrations: *Physics* II.2 (193b23), *Metaphysics* XIII.3 (1078a14), *Posterior Analytics* I.10 (76a10—25), and *Posterior Analytics* I.13 (78b35—79a15). The persuasiveness of Lennox's claim in the quotation above varies with the different fields of study it is applied to because Aristotle treats the four different fields differently with regard to mathematics. The claim that optics is mathematical, for instance, is not controversial because in *Posterior Analytics* I.14, Aristotle gives three examples of mathematical sciences: "arithmetic and geometry and optics" (79a16). This leaves the question about the status of the remaining sciences mentioned: mechanics, astronomy and harmonics.

In footnote 7, Lennox (1986) supports his claim that mathematics is essential to Aristotle's science by citing several passages from Aristotle. The first is from *Physics* II.2, where Aristotle says "…the more natural of the branches of mathematics, such as optics, harmonics, and astronomy” (Hardie and Gaye, trans., 1984, 194a7). Taken with the passage from *Posterior Analytics,* this passage from *Physics* could be understood to mean that Aristotle thinks that arithmetic, geometry, optics, harmonics, and astronomy, just *are* mathematical sciences; but, it is made less clear by calling them ‘natural’. They are tied both to the natural world and to mathematics, but this passage does not do the clarifying work that Lennox would like. The Greek text translated by Hardie and Gaye as “the more natural of the branches of mathematics” is “*ta phusikôtera tôn mathêmatôn*”. ‘Branches’ is an over-translation; it should not be inferred from this passage that these sciences are ‘branches’ of mathematics in the same way that geometry and arithmetic are. Lennox needs to clarify exactly how the empirical content is introduced and combined with mathematical propositions in the mathematical empirical sciences.

The second passage Lennox (1986) cites is *Metaphysics* XIII.3:

> Thus a science which abstracts from the magnitude of things is more precise than one which takes it into account; and a science is most precise if it abstracts from movement, but if it takes account of movement, it is most precise if it deals with the primary movement, for this is the simplest; and of this again uniform movement is the simplest form. The same account may be given of harmonics and optics for neither considers its objects *qua* light-ray or *qua* voice, but *qua* lines and numbers; but the latter are attributes proper to the former. And mechanics too proceeds in the same way. Thus if we suppose things separated from their attributes and make any inquiry concerning them as such, we shall not for this reason be in error, any more than when one draws a line on the ground and calls it a foot long when it is not; for the error is not included in the propositions. (Ross, trans., 1984, 1078a14)

This again claims that harmonics and optics are mathematical; however, in this case it is clearer how empirical observation plays a role. The *objects* of optics and harmonics are rays and sounds, but not *qua* rays and sounds, instead rays and sounds *qua* lines and ratios. In the *Posterior Analytics* I.10, Aristotle says that “harmonical theorems are proved through arithmetic” (76a10-25). It could be extrapolated from this that some of the objects of mechanics are the abstracted properties of bodies capable of movement.

Lennox (1986) summarizes the position he thinks is based on common misconceptions or incorrect assumptions about Aristotle’s philosophy of mathematics, which he later criticizes:

> (i) Aristotle holds that physical objects do not perfectly instantiate mathematical properties. (ii) Therefore, he [Aristotle] holds that the objects of mathematics are abstractions, things apart from the changing physical world. (iii) But if so, physics and mathematics study two distinct kinds of objects. (iv) Therefore, in Aristotle’s philosophy of science, neither can serve as the source of explanatory principles for the other. … Convinced by this argument, one might very well see Aristotle’s discussion of the mixed sciences (our term, not his) as fundamentally inconsistent with this philosophy of science. (p. 32)

Lennox claims that the argument in the quotation fails because he believes that Aristotle would reject the first premise. Lennox does not immediately support this assertion, so we will look further for his argument.

Lennox’s approach to explain Aristotle’s distinction between things that are properly separable in thought and things that are not, is in terms of essences. Lennox suggests that the difference lies in the fact that circles, for example, are not essentially bronze or silver or wooden, etc., whereas presumably souls are essentially linked to bodies for Aristotle, such as human and animal souls.[45] Lennox (1986) explains the difference between bronze circle and souled animal:

> A common suggestion is that circles, being abstract objects, are only incidentally found in various materials...I would like to offer a different reading. Circles are not *essentially* bronze (or silver, or chalk, or flesh). Aristotle insists that circles must be of *some* material or other, but not that they are essentially of a specific material. (p. 34)

If Lennox is right about Aristotle's distinction, then Aristotle is saying that circles are *necessarily* embodied, but that circles are only *contingently* embodied in any particular material. This is not true with animals for instance. The same animal could not be made out of fire as the one made out of earth, water, air, and fire in the right mixture to produce bones, flesh, etc.

Lennox is trying to express that there is a difference in the way the form of mathematical objects inheres in material from the way souls inhere in material. The difference is that one cannot understand an animal without including an account of the animal's perceiving, changing, etc. according to its function, and that this understanding is only possible because of the animal's matter. Mathematical objects, on the other hand, do not have functions, they certainly do not change; furthermore, they do not change precisely because their matter is only incidental to them even though every circle exists in some material and every soul exists concomitantly with some material.

We have been trying to get at how mathematical propositions (or objects) can inform the empirical sciences in Aristotle's system. Aware that there seem to be

[45] cf. *De Anima*.

exceptions to almost every rule in nature, Aristotle says that scientific generalizations are true "always or for the most part." The question is – where does the indeterminacy enter and why in the physical sciences? Mathematics is a desirable paradigm for the sciences in no small part because there are not exceptions to proven propositions in mathematics. Perhaps the reason for this and the reason that math can serve to inform the empirical sciences is that, as Aristotle claims, change is only possible in matter, but mathematical objects are not essentially tied to any specific material. Since we encounter mathematical forms, for instance when we see a bronze sphere, it is clear that mathematical objects exist in some sense in nature for Aristotle. Since mathematical objects are not inherently tied to a particular material, what is true of an instantiated mathematical object of bronze, must also apply to instantiated mathematical objects of wood. So what the mathematician works on is the immutable, eternal truths about the forms of mathematical objects. This is just the same in empirical scientific investigation; for instance, the biologist is also trying to learn about the immutable *forms* of her subject. Aristotle is attempting to achieve the level of epistemic justification in mathematics in the empirical sciences. It could work in the following way: if a mathematical object is instantiated in nature, then the properties that are true of the form must be true of the material it is in to the extent to which it does in fact inhere in the material. So, a particular sphere is not eternal insofar as it is a bronze sphere, for instance, but it is round say insofar as it is a sphere. Further, insofar as it is a sphere we can know that it only touches a flat surface at one point, or we could say the closer the sphere approximates to the form of sphere the closer it will be to touching at only one point.

So, if Aristotle can demonstrate that the rainbow is the instantiation of an arch, which has a semicircle as its upward measure limit, then we can be as epistemically justified that rainbows cannot be greater than 180 degrees as we are certain that the rainbow is an instantiation of such an arch.[46]

So far we have looked at Aristotle's formal account of his concept of scientific explanation, two case studies from Aristotle's science writings, and the role of mathematics in Aristotle's scientific explanations. Next we will give a broader analysis of how Aristotle generates new scientific explanations. We will also highlight some of the inherent problems in Aristotle's system, which will make Galileo's methodological departures from Aristotle clearer in the chapter 4 discussion below.

2.5 Analysis of Method for Generating Scientific Explanations

Crombie (1953) describes Aristotle's scientific method as a two-part process: inductive and deductive. Induction here refers to the process of forming generalizations based on an unspecified size set of particular observations.[47] Deduction refers to logical entailment from premises that are a mix of generalizations and empirical facts about particulars. Crombie's view of Aristotle's scientific method is that students of nature

[46] It is more cumbersome, but perhaps more accurate to say that Aristotle's challenge is to demonstrate that the rainbow is the instantiation of the cross-section of a cone, which itself is cut by the horizon, and the maximum measure of the arch of the visible conic section is 180 degrees.

[47] My summary here of the historical understanding of induction follows Vickers (2006): "until the middle of the previous century induction was understood to be what we now know as enumerative induction or universal inference; inference from particular instances: $a_1, a_2, \ldots, a_n$ are all Fs that are also G, to a general law or principle all Fs are G" (p. 1). However, the bigger question for evaluating Aristotle's method is whether he intends his generalizing mechanisms to be inferential at all. Hankinson (1998) argues that what appear to be inductive steps for Aristotle are not really meant to be inferential (p. 168). This would be a significant problem for Crombie's account of Aristotle's method, because Crombie implies that Aristotle's process of discovery is inductive in the classical sense of induction.

begin with sensory observations and then "ascend by induction to generalizations or universal forms or causes" that are more remote from experience. They then "descend again by deduction from these universal forms to the observed facts" (1953, p. 25). If Crombie's two-step process is correct, then there is a problem for Aristotle's method—specifically in the demonstration of new knowledge—because a successful deduction from assumed hypotheses does not prove that the assumed hypotheses are true.[48]

One potential problem for Crombie's account of Aristotle's method concerns whether Crombie is correct to call Aristotle's first step 'inductive'. Crombie (1953) explains his understanding of Aristotle's process:

> Of the inductive process by which the investigator passed from sensory experience of particular facts or connexions [sic] to a grasp of the prior demonstrative principles that explained them, Aristotle gave a clear psychological account. The final stage in the process was the sudden act by which the intuitive reason or *noûs*, after a number of experiences of facts, grasped the universal or theory explaining them, or penetrated to knowledge of the substance causing and connecting them. (p. 27)

Crombie's phrase "after a number of experiences" in the excerpt above comes from Aristotle's claim in *Posterior Analytics* I.31, that "it is from many particulars that the universal becomes plain" (Barnes, trans., 1993, 88a2). What Aristotle means by the claim that the universal becomes clear, "from many particulars" is not immediately obvious. "After a number of experiences" could mean that Crombie thinks Aristotle requires a certain number of experiences in order to be justified in claiming the universal. This interpretation of Crombie's account would explain why Crombie calls the process of

[48] For a simple illustration consider the following valid but unsound argument that has a true conclusion: P1. Socrates is a philosopher; P2. All philosophers have legs; Therefore C1. Socrates has legs.

moving from experiences of particulars to universals ‘induction,’ in the classical sense.

The problem is that Aristotle is not thinking in terms of induction; that is, Aristotle does not think the validity of the move from particulars to universals is systematically based on the number or quality of the observer’s experiences. Aristotle does not explain how we can be certain of universals *reached* from experiences of particulars, but Aristotle does seem to think that this is what it means to have an intuitive intellect, i.e. *nous*: humans just are good at coming to understand the form, i.e. the universal, from encounters with particulars. Some evidence for the claim that Aristotle’s process here is not inductive, in the classical sense, is that he never discusses how many experiences are necessary to know a universal nor does he say that more experiences will lead to greater epistemic certainty or better understood universals.[49]

In Crombie’s characterization of Aristotle’s system, the generalizations reached by induction serve as the premises from which the particulars that we observe are supposed to be ultimately derivable.[50] Crombie (1953) explains that this is the second part of Aristotle’s method:

> The second process in science was to descend again by deduction from these universal forms to the observed facts, which were thus explained by being demonstrated from prior and more general principles which were their cause. (p. 25)

By Crombie’s account of Aristotle’s method, Aristotle uses the fact of a successful

[49] Aristotle is not worried about the epistemology of universal acquisition the way Modern and contemporary thinkers are. He is not worried about proving whether or not he has the right universal or qualifying explanations based on his level of certainty. For instance, in the *Critique of Pure Reason,* Kant criticizes what he calls the haphazardness of Aristotle’s epistemology; see discussion in chapter 4.6.
[50] This is why Crombie says that Aristotle’s process of scientific discovery is inductive.

deduction from the universals he is trying to discover to lower level universals and ultimately empirically observed particulars as evidence for the veracity of those universals. However, this constitutes a logical problem for Aristotle's demonstrations. For something properly to be called knowledge, it must be demonstrable from known premises. Given a valid deduction, if the deduction leads to something known to be false or impossible, then we can know that at least one of the premises is false since it is not possible to deduce a false proposition from true premises through valid reasoning. Hence, from an unsuccessful deduction we have the potential to learn a negative fact. However, if the deduction does not obviously fail then we still cannot be sure of the truth of the premises upon which the deduction is made. In other words, in the case of an apparently successful deduction nothing is revealed about the truth value of the premises, because it is possible to arrive at a true conclusion from false premises.

Although ultimately incomplete, Crombie's account of Aristotle's scientific method is useful for drawing our attention to this potential problem with Aristotle's demonstration of new scientific explanations. If this problem is irresolvable, then it will evince a significant gap between Aristotle's description of the scientific process in *Posterior Analytics* and his actual scientific practices.

Barnes (1993) offers a fuller explanation of Aristotle's scientific process. In the introduction to his translation of the *Posterior Analytics*, Barnes says that Aristotle's scientific method consists of three parts: "First, we collect the facts. Secondly, we look for the explanations. Thirdly, we construct the demonstrations" (p. xx note A). Barnes's being explicit about the first step of gathering data is not at odds with Crombie's account even though Crombie takes this step for granted.[51] The second step that Barnes identifies in Aristotle's method is looking for the explanations. This is the step where universals are in some way determined from the observational data. The third step for Barnes is demonstration, which is analogous to Crombie's stage of deduction.

It is significant that Barnes remains more general, less restrictive than Crombie about the form of reasoning Aristotle uses and more specific about what is learned in each step. Barnes' description is vaguer because he does not identify the type of reasoning Aristotle uses; however, Barnes' description is less flawed for the same reason. Barnes allows for the idea that Aristotle would not agree that the way the student of nature moves from particulars to universals corresponds precisely to our contemporary concept of induction.

Barnes argues that Aristotle's intention is to axiomatize the sciences; i.e. that Aristotle tries to model the empirical sciences on mathematics, in the sense of starting from first principles and then deducing further principles. However, there is an important difference between the empirical sciences and mathematics. In geometry, for instance, the axioms can be given before the discovery and demonstration of new theorems,[52]

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[51] Barnes is using the term 'facts' appropriately for contemporary science; he is referring to the things empirically determined, which can be true or false. This is contrasted with common parlance, which gives 'facts' the connotation of being the most certain things, independently of how they are established. Unlike Aristotle, we have inherited a substantial tradition of empiricism (and skepticism). However, if we take Aristotle at his word, the facts of the observational data variety are not the kinds of things that Aristotle thinks are ultimately the most knowable, although they *are* most knowable to us.

[52] This is true of a 20th century description of mathematics, where any particular geometry, for instance, is defined by a set of axioms which then necessarily lead to an internally consistent set of consequences. This can be seen, for instance, in plane geometry where the axioms entail that the interior angles of every triangle equals two right-angles, and every other proposition. Euclid's *Elements* begins by stipulating definitions, axioms and the most elementary constructions. From these, the rest of geometry is a set of deductive consequences. What is less helpful about this 20th century description of geometry is that it does not illuminate what ancient mathematicians saw themselves as doing. Euclid *et al*. may have thought they

whereas in empirical science we must use the processes of discovery and demonstration even to determine the first principles of each science.[53] The problem here is that in Aristotle's science it is precisely the fundamental axioms we are looking for. How can Aristotle come up with these axioms for the empirical sciences?

Aristotle's goal is to get justifiable epistemic certainty of the universals, which he thinks are logically prior to the observed phenomena in the sense that they are explanatory of them, though they are not temporally prior to them. Because for Aristotle all knowledge about nature begins with sense data, knowledge of universals must be arrived at through experience. This is a problem because it is impossible to know whether or not future experiences will undermine or contradict the universals.

Another difficulty with Aristotle's approach is that there can be multiple conflicting universals that seem to explain the same phenomena. Aristotle's system cannot distinguish among conflicting universals. Consider the following fictional example: Two Aristotelian observers record the fluctuation of the change in ocean height (tidal phenomena) and try to reason to the universal that explains the phenomena. The first thinks the tides are caused by the winds; this is apparent because we observe that waves are generally greater on windy days and calmer on less windy days, hence the wind is what moves the waters, and must then also be moving the waters to cause the

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were discovering mathematical truths perhaps by beginning with particular empirical observations and reasoning to general mathematical rules (Boyer, 1991; Rudman, 2007; Berlinghoff and Gouvêa, 2002). Examples of this in ancient mathematics include the different approximations for π arrived at after observing a regular relationship between diameter and circumference, congruence rules, etc. (Boyer, 1991). The *Elements* is not a book that reveals the process of mathematical discovery. Instead it is the codification of geometry after it had been worked out.

[53] I am referring to the first principles proper to each science and not first principles of all science, e.g. the law of non-contradiction.

tides. The second observer thinks the tides are caused by heavenly bodies; this is apparent because we observe the correlation between the Moon's movement and the tides.[54]

This gives us two competing explanations of tidal phenomena. The first observer comes up with deduction (E):

(E) All Risings of Water are caused by the Wind
All Tides are Risings of Water
thus, All Tides are caused by the Wind.

The second observer comes up with deduction (F):

(F) All Risings of Water are caused by the Moon
All Tides are Risings of Water
thus, All Tides are caused by the Moon.

The second observer could also move back in the order of explanations by making a syllogism using the fact that the heat of heavenly bodies moves water to get to the Moon's causing of the tides.

(G) All Risings of Water are caused by the heat of the heavenly bodies
All Tides are Risings of Water
thus, All Tides are Risings of Water caused by the heat of the heavenly bodies.[55]

[54] The possible mechanism for this might be suggested by Aristotle pointing out that the heat of the Sun is what is responsible for water evaporating, which is what allows it to rain. (*Meteorology*, II.4., 360a1) The second observer knows, as Aristotle says, that the Moon has less heat than the sun, but it still has some heat, much more than the stars for instance. Knowing that the great heat in the Sun raises the water into the sky, the second observer reasons from this that the heat of the Moon is sufficient to raise the water, but not sufficient to evaporate it, so the water level rises; hence the tides

[55] Properly, to deduce the tides from the Moon's heat we would have a chain of two syllogisms: The first showing that the Moon has heat because it is a heavenly body, all of which have heat, and the second showing that the Moon's heat raises the tides.

In these examples the observers have moved from specific observations of daily changes in water level to generalizations about the tides and then to higher order generalizations that are meant to entail the lower order generalizations. Both observers can successfully deduce the cause of the tides. However, these deductions cannot both be demonstrations of the tides according to Aristotle, because they invoke contradictory premises: (E) claims that tides are exclusively caused by the wind, and (F) and (G) claim that the tides are exclusively caused by the heat of heavenly bodies. Thus, a problem is revealed: even if it were true that observation could reveal that the wind or heat of heavenly bodies caused tidal motion, it could not be observed that this was the *only* cause of the tides.

Aristotle assumes that, in general, we are able to discern the correct universal from among the *logically* possible universals. Aristotle is often aware of possible competing explanations, but does not carefully address the discrimination problem. In fact, Aristotle often begins his scientific investigations by considering all previous differing explanations of phenomena offered by other thinkers. From what others have said and from what he has observed and reasoned, Aristotle tries to figure out the right explanation.[56] It would be nice if he said more about leaving his principles open for refinement as new data is introduced, but the fact that he does not do this further evinces that he is not thinking about induction in the classical way. Aristotle apparently thinks

[56] Owen (1961) argues that Aristotle's claim that knowledge in any given science begins with the *phainomena*, is incorrectly understood to mean that Aristotle believes every science begins with empirical observations. "The phainomena to which the Physics pays the most attention are the familiar data of dialectic, and from the context in the Prior Analytics it seems clear that Aristotle's words there are meant to cover the use of such data. For in concluding the passage and the discussion in which it occurs Aristotle observes that he has been talking at large about the ways in which the premises of deductive argument are to be chosen; and he refers for a more detailed treatment of the same matter to the 'treatise on dialectic' (A.Pr. I 30, 46a28-30). He/ [sic] evidently has in mind the claim made in the Topics that the first premises of scientific argument can be established by methods which start from the endoxa" (p. 244).

we should not make a judgment until we know we have the right universal, which he thinks we just know to be true when we know it.

Aristotle gives examples of competing explanations, for instance, when he explains the cause of thunder. When the warm dry air is squeezed out of clouds by cold air, the dry air runs into neighboring clouds, and the impact it makes is what we call thunder (*Meteorology,* II.9, 369a30). Aristotle also brings up two other possible explanations for thunder, and then explains why they are wrong. According to Aristotle, Empedocles and Anaxagoras believe there is fire in the clouds and that thunder is the hissing noise when this fire is extinguished. Aristotle rejects this explanation because it does not explain why lightning moves contrary to the direction that fire moves by nature (369b22).[57] Here we see an implicit criterion Aristotle uses for discriminating among possible explanations: one explanation is better than another if it accounts for more phenomena, i.e. has broader explanatory power. This criterion is also consistent with conditions (v) and (vi) above, which require that the principles used in demonstrations have the broadest explanatory power possible. However, we have seen that this is vague and eminently fallible. At *Meteorology* I.7 Aristotle says that, "We consider a satisfactory explanation of phenomena inaccessible to observation to have been given when our account of them is free from impossibilities" (Webster, trans., 1984, 344a5). Aristotle does not argue that the competing explanations of thunder fail because they involve impossibilities. However, strictly speaking, all three explanations are satisfying

[57] Here Aristotle uses 'explanation' as an example of the definitional introduction of middle terms, which he discusses in *Posterior Analytics* II.7.

in that they are free from impossibilities.[58] He calls them implausible and explains why his explanation is more satisfying. It is curious that in his discussion of the competing explanations, of thunder for instance, Aristotle does not spend greater time discussing the possibility of error in his system and how to treat it.

To head off a potential misunderstanding it needs to be noted that the idea of discriminating among possible universals that account for particular phenomena is not a matter of picking from a list of different universals all of which are possibly true, or could have been true. ‘Possible universals’ just refers to the fact that we can imagine all sorts of things that might causally explain phenomena, we just cannot always know that one is right just because we think it is.[59] The following passages evince the idea that the universals we are looking for, the ones that we can use in scientific demonstrations, are necessarily true: “the object of scientific knowledge is of necessity” (*Nicomachean Ethics* VI.3, Ross, trans., 1980, 1139b21); “what you understand cannot be otherwise” (*Posterior Analytics* I.6, Barnes, trans., 1993, 74b6). These quotations point to Aristotle’s belief that the universals we find must be necessary in the sense that universals cannot be essentially accidental. Universals must be necessarily true because the principles of nature are unchanging to Aristotle (*Physics* I.5).

However, just knowing that universals must be necessary does not help us with the problem of how we identify the true universals. The fundamental problem remains: reasoning from a universal (mathematical or otherwise) that necessitates, for instance,

[58] I might be overstating this claim. From Aristotle’s perspective it may be that Anaxagoras’ theory is incompatible with a reasonable account of the direction of lightning, and hence impossible.
[59] cf. *Posterior Analytics* I.6, for Aristotle’s discussion about the necessity of premises in a demonstration.

that the rainbow's arc is a maximum of 180 degrees, to observational data does not guarantee the truth of the universal, even if our observations about the degree measure are robust. Aristotle never resolves this problem of determining epistemic warrant. Of course, this is a problem for contemporary model building in the sciences as well. This is part of why it is impossible to achieve justified epistemic certainty about our explanations of natural phenomena. Because contemporary theory building remains shackled to induction, contemporary theories remain defeasible.[60,61]

Above we discussed a problem with Aristotle's attempt at using mathematical demonstrations to serve as a models for demonstrations in the empirical sciences: the problem was with justification, and we tied the problem to empirical investigation's requirement of induction. It should now be clearer why this problem arises in Aristotle's system. The distinction between mathematical objects and empirical objects discussed above reveals why mathematical objects are not susceptible to problems with induction—they do not essentially involve physical material, i.e. the stuff that allows for change. So, it is not a problem to let one figure represent all triangles, for example. There is no error generated by this, whereas with natural objects, we have to make observations even to generate the first principles of particular sciences. In geometry one can be certain by definition that all plane triangles are three-sided rectilineal figures before one investigates the interior angle-sum of triangles. Thus, this is a problem for Aristotle's scientific demonstration in the sense of using mathematics as a model for scientific demonstrations in the empirical sciences.

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[60] However, contemporary accounts of induction are broader than the classical model. See chapter 5.
[61] This is also the reason why Scientific Realism is not epistemically warranted.

The problems for Aristotle's concept of scientific demonstration discussed here—epistemic justification of universals, discriminating among competing universals, and the limitations of applying mathematical techniques to empirical science—are not resolved by Aristotle. If we follow suggestions to return certain elements of Aristotle's concept of scientific explanation to contemporary models of explanation (e.g. Brody, 1972), then we will need to address these potential problems. It is necessary to address these problems because, although adding Aristotelian essence and causation to contemporary models of scientific explanation might give greater intuitive satisfaction to some scientific explanations, there is also the potential that adding these elements could actually undermine the epistemic warrant of the explanations that Brody is trying to improve.

Aristotle's concept of scientific explanation has had a profound impact on the history of science. His ideas were passed down through antiquity to Arabic scholarship and then reintroduced to the Latin West in the late Middle Ages. Although intervening thinkers modified how Aristotle's concept of scientific explanation was applied, it is still thought of as the standard account during Galileo's time. Galileo himself tries to take the best of Aristotle and exclude what he finds less helpful (see chapter 4). Galileo makes the distinction between Aristotle's methods and his findings. However, Galileo's self-named Aristotelian contemporaries had moved far from the ideals of Aristotle's concept of explanation (such as careful observation followed by rigorous demonstration), and instead embraced history's understanding of Aristotle's particular findings (e.g. that the heavier body falls faster than the lighter body in the ratio of their weights). In fact, Galileo claims that the 17th century Aristotelian view is that all knowledge about nature is already contained in Aristotle's corpus.[62] Whether the ideal of Aristotle's concept of explanation is something actually attainable in scientific practice will be taken up in chapter 5, after we have discussed what Galileo's departure from Aristotle and the Aristotelians consisted of. Next we will look at the incremental progression from Aristotle to Galileo in order to establish the basis of knowledge environment in which Galileo built his concept of scientific explanation.

[62] See Dialogue "Second Day," Drake, 1981, p. 126; "Third Letter on Sunspots," Drake, 1957, pp. 126-7.

Chapter 3. Developments in Scientific Explanation in the Period between Aristotle and Galileo

3.1 Introduction

This dissertation investigates the most crucial change between Aristotle and contemporary science, namely, Galileo's work. The purpose of this chapter is to highlight some of the developments in the method of investigating nature that occurred between Aristotle and Galileo in order to understand better just what is revolutionary about Galileo's concept of scientific explanation.

Understanding Galileo's contribution to the theory of scientific explanation requires that we understand what he built upon and changed. The story is complicated for several reasons. First, the self-named Aristotelians of Galileo's time thought very different things from Aristotle himself. Second, not surprisingly, what it meant to be an Aristotelian changed in significant ways over the 1900 years between Aristotle and Galileo. Third, current scholarship mistakenly attributes to Galileo ideas that developed from Aristotle and the knowledge context of Aristotle's time, while at the same time, it misunderstands how, exactly, Galileo revolutionized empirical science, especially scientific explanation. Büttner *et al.* (2002) notes this common misconception:

> When historians of science discuss the general state of ideas in the seventeenth century, they tend to portray medieval Aristotelian scholasticism merely as the counter position against which Galileo's theory of motion gained its profile as a new science, neglecting the potential of Aristotelianism as a generic knowledge resource available to Galileo and his contemporaries. (p. 11-12)

As the quotation suggests, it is a mistake to assume that all of Galileo's ideas sprung from him *sui generis* and that they are directly opposed to Aristotle's. However, Galileo did revolutionize scientific inquiry by increasing empirical rigor through quantifying experimental observations and by constructing predictive mathematical models. In order to gain a more nuanced understanding of the relationship between Galileo and Aristotle, this chapter discusses the developments in empirical scientific investigations in general, concepts of scientific explanations in particular from Aristotle to Galileo and the knowledge environment present for Galileo. Discussing the differences between Galileo's and Aristotle's concepts of scientific explanation will provide a context for evaluating the appropriateness of returning some elements of Aristotle's concept (essence and cause) to contemporary models of scientific explanation.

Like Büttner *et al.* (2002), Crombie (1953) defends the position that the Modern approach to empirical scientific investigation did not emerge whole from Galileo. In fact, he goes much further:

> The experimental method was certainly not completed in all its refinements in the thirteenth or even the fourteenth century. Nor was the method always systematically practised. The thesis of this book [*Robert Grosseteste and the Origins of Experimental Science 1100—1700*] is that a systematic theory of experimental science was understood and practised by enough philosophers for their work to produce the methodological revolution to which modern science owes its origin. (p. 9)

The latter quotation suggests that, instead of thinking of Galileo as the architect of the Scientific Revolution, it may be more accurate to think of Galileo as having put the final piece in a puzzle begun much earlier, the completion of which marked the full evolution into Modern Science.[63]

Section 3.2 briefly outlines the evolution of Greek science after Aristotle by concentrating on the work of a few natural scientists: Archimedes, Eratosthenes, and Ptolemy. Section 3.3 looks at the early medieval period, essentially from the fifth to the early twelfth century. Although the emphasis on the investigation of nature declined during this time there were some scholars, the Encyclopedists, who collected and passed down versions of earlier work. Section 3.4 looks at the birth of Aristotelian Scholasticism, the period when Aristotle's logical treatises, along with some ancient Greek mathematical texts, were translated into Latin. Useful figures to consider during this time include Robert Grosseteste, Theodoric of Freiberg, and Adelard of Bath. Section 3.5 considers Copernicus' direct impact. Section 3.6 considers the question of the impact on Galileo of the common or shared knowledge of his time.

3.2 Greek Science in the Period after Aristotle until the Early Middle Ages Expanded the Role of Mathematics in Empirical Demonstrations

This section examines elements of scientific demonstration in the ancient world after Aristotle. Instead of ending with Aristotle, the use of mathematics in scientific demonstrations expanded in proceeding centuries. Aristotle is explicit that he wants to

[63] This sounds dramatic; however, more accurately would be to say that Galileo put in a very significant methodological piece and Kepler supplied a significant mathematical model piece, both of which allowed Newton to finish the puzzle, i.e. codify modern science with the *Principia*.

model empirical demonstrations on mathematical demonstrations. Lloyd (1973) explains how this tradition grew:

> But it was mathematics that provided, in the third and second centuries, the finest examples of the systematic demonstration of a body of knowledge. The clear and methodical presentation of proof in Euclid, Archimedes and Apollonius became the model for the rest of Greek science. (p. 52)

There is an important distinction, not clear in Lloyd's treatment, which needs to be made. It is one thing to model the *forms* of demonstrations on mathematics but quite another to embody mathematics as a part of the structure of nature. This distinction is often blurred and some ancient natural philosophers went much further than Aristotle in basing their confidence in their demonstrations about the empirical world on their metaphysical commitments to the idea that the natural world is mathematical in structure.

For example, the substantial and varying uses of mathematics in Archimedes' (287-212 B.C.E.) corpus demonstrate that at least some natural philosophers continued to construct mathematical accounts of empirical phenomena. In *The Method*, a short treatise that Archimedes wrote to Eratosthenes, Archimedes suggests the benefits of using the empirical science of mechanics to aid in solving mathematical problems:

> I thought fit to write out for you and explain in detail in the same book the peculiarity of a certain method, by which it will be possible for you to get a start to enable you to investigate some of the problems in mathematics by means of mechanics. This procedure is, I am persuaded, no less useful even for the proof of the theorems themselves; for certain things first became clear to me by a mechanical method, although they had to be demonstrated by geometry afterwards because their investigation by the said method did not furnish an actual demonstration. But it is of course easier, when we have previously acquired, by the method, some

> knowledge of the questions, to supply the proof than it is to find it without any previous knowledge. (Heath, trans., 1953, p. 13)

By "mechanical method," Archimedes is referring to using physical structures and relationships to suggest hypotheses that will then be demonstrable in mathematics. Archimedes makes two provocative claims about what can be gained by applying a "mechanical method" to help solve mathematical problems. The weaker claim is that mechanical examples are helpful by *suggesting* new mathematical hypotheses. The much stronger claim, which is not immediately defended by Archimedes, says that mechanical examples can even furnish the proof of mathematical theorems. With the first claim, Archimedes is revealing one of his methods for beginning the discovery phase in mathematics, i.e. analysis. First we will look at Archimedes' example and then two simplified examples to illustrate Archimedes' idea of using empirical trials to inform mathematics.

In the *Method*, Archimedes gives the following as the first example of a mathematical theorem suggested to him by a mechanical method: "Any segment of a section of a right-angled cone (i.e. a parabola) is four-thirds of the triangle which has the same base and equal height" (Heath, trans., 1953, p. 14). See Figure 3.1.

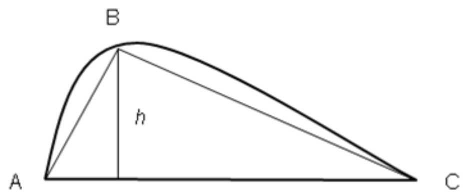

Figure 3.1
The segment bounded by Parabola ABC and Chord AC is 4/3 the Triangle with base AC and height *h*.

The claim is that given any segment of a parabola, the area of the segment will be equal to 4/3 the area of a triangle with the same length base and height as the parabolic segment. Archimedes works through the reasoning for this theorem as though the lines were weights on a lever and determines by the ratio of these lines what must be the ratio of the segment of the parabola to the triangle of equal base and height. In this process Archimedes is treating mathematical objects as physical objects, weights on a lever, and is looking for the combination that will balance the lever. In this physicalization of mathematical properties, a balanced lever indicates an equality—Parabolic Segment ABC = 4/3 Triangle ABC.

To further clarify how Archimedes's mechanical method might be used to generate mathematical hypotheses, consider the following example. Playing with different weights on a lever one begins to recognize that a smaller weight will balance a larger one if the smaller weight is further from the fulcrum than the larger. A careful observer may begin to see a relationship between the magnitudes of the weights and their distances from the fulcrum. A careful observer such as Archimedes, will start to get ideas about what the relationship might be and come up with the idea that weights balance at distances from the fulcrum inversely proportional to their magnitudes—the law of the lever. Archimedes determined that weights will balance on a lever if the following ratio holds between the weights and distances from the fulcrum on the two sides: A : C :: D : B. See Figure 3.2.

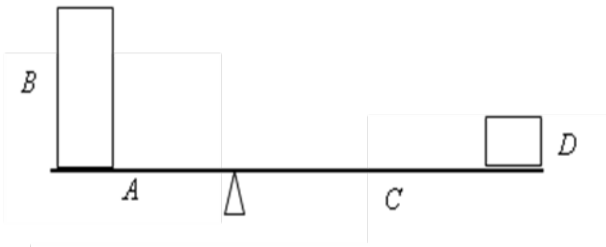

Figure 3.2
A is the distance from the fulcrum to the weight *B*
C is the distance from the fulcrum to the weight *D*

From the mechanically arrived at idea of balancing weights, one might ask if there is a lesson in this for mathematics. The analogy might suggest itself as follows: weights and distances balancing other weights and distances is like a two-dimensional figure being equal to another two-dimensional figure. If we treat the two magnitudes from each side of the lever as two magnitudes in general or if we treat only their values and do not worry about their units, or treat both as lengths, then we could suggest that the two factors, weight and distance, are two lengths producing a rectangle. Then the law of the lever would suggest that rectangles are equal when they are in a ratio satisfying the law of the lever such that A x B = C x D, which turns out to be true when these magnitudes are in the ratio of A : C :: D : B. This example with weights on a lever illustrates using mechanical practice as a means of generating a new hypothesis in mathematics.

The next example as well illustrates mathematical hypotheses generation but also gives some insight into Archimedes stronger, more inflammatory claim in the quotation above that says mechanics can supply *proof* of mathematical theorems. Beginning with three fixed lengths, such as sticks, one wonders how many different triangles could be made. If more than one triangle can be made from the same three lengths, then having congruent sides would not be a condition of congruency between triangles. On the other hand, if only one triangle can be made from the same three sticks, then one could suppose that different three sided figures having three equal sides (sometimes called side-side-side) will be both a necessary and a sufficient condition for two triangles being congruent. More technically stated the question is: Are triangles that are reflections through a single axis of symmetry congruent? With three sticks one can see that only one triangle is possible. Thus, we have used a "mechanical method" to suggest the hypothesis that three specific lengths will always yield congruent triangles. Having discovered this idea empirically, and thereby having some evidence for the truth of the hypothesis, we could then devise a geometrical demonstration of this, for instance something like propositions I.7 and I.8 in Euclid's *Elements*.[64] These examples illustrate that one of Archimedes's methods of discovery in mathematics, i.e. the analysis process, relies on being able to infer mathematical propositions from natural phenomena.

Heath (1953) points out the significance of Archimedes' discussion about the discovery phase:

[64] Archimedes does not explain exactly how physical objects could demonstrate a mathematical proposition; however, this illustration suggests that the force of such a proof would come from not being able to imagine a counterexample, i.e. some other possible arrangement of the same three sticks that did not yield a congruent triangle. Archimedes' mathematical proofs are rigorous; he knew that mathematical demonstrations could not be based on a few specific examples. His proofs are either direct proofs about the general case (i.e. not particular objects) or they are *reductios ad absurdum*. Archimedes may have dropped the discussion about physical proofs for mathematical hypotheses because they would lack rigor.

> Nothing is more characteristic of the classical works of the great geometers of Greece, or more tantalizing, than the absence of any indication of the steps by which they worked their way to the discovery of their great theorems. … As they have come down to us, these theorems are finished masterpieces which leave no traces of any rough-hewn stage, no hint of the method by which they were evolved. A partial exception is now furnished by the *Method*; for here we have a sort of lifting of the veil, a glimpse of the interior of Archimedes' workshop as it were. (p. 6-7)

Chapter 2 discussed a difficulty for our understanding of the ancient analytic process: it is not clear how to describe the process of devising new hypotheses or how to construct the demonstrations that turn the hypotheses into theorems. Although nothing like a rigorous explanation or codification of the process is given, it is still helpful that, unlike Euclid, Pappus,[65] and seemingly the rest of the ancient mathematicians, Archimedes gives us a hint of how he discovers new hypotheses by using a mechanical method.

Archimedes' empirical discovery method for mathematics reveals his metaphysical commitment to the mathematical character of the world. Archimedes' work implies that he believes that if a proposition holds in the empirical world then it must also hold in mathematics. This is implied, for instance, by his use of weights on a lever to arrive at the quadrature of the parabola. Archimedes is also committed to the notion that mathematics can inform demonstrations in the empirical sciences: he reports that he uses geometry to solve problems in mechanics and statics (Lloyd, 1973, p. 46). Archimedes's work implies one of the following two commitments: either it is the case that if a proposition holds in mathematics then it must also hold in the empirical world; or the

[65] Pappus of Alexandria (c. 290- 350 C.E.) contributed to ancient geometry through original proofs as well as by systematically organizing, and insightfully commenting on the greatest works of geometry in the preceding six centuries. His best known work, only partially preserved, is *Synagoge* (translated as *Collection* or *Mathematical Collection*).

weaker commitment, that if a proposition holds in mathematics then it cannot be false in the empirical world, i.e. there could be no physical counterexamples. It is not just that empirical sciences and mathematics suggest hypotheses for each other; Archimedes treats mathematics as providing a demonstration, i.e. the rigorous proof of theorems that are true both in mathematics and nature. For instance, in *On Floating Bodies*, Archimedes mathematically demonstrates relationships among weights of bodies and displaced fluids, as well as the lever and statics.

The suggestion that mathematics can ‘prove’ something about physical objects is alien to the contemporary reader; indeed, how can mathematics itself prove physical facts? We treat things like the law of displacement for floating bodies and the law of the lever as *empirical* facts; thus, for us it is not a matter of what holds in mathematics but just a matter of whether or not objects do behave a certain way; e.g., whether a body of twice a given mass balances that mass at twice the distance from the fulcrum. Furthermore, in principle at least, we accept that this *law* only holds until some further observational data comes along that suggests a better hypothesis. We balk at Archimedes’ use of mathematics in the empirical sciences in part because we now have many different branches mathematics which are sometimes incompatible such as: Euclidian geometry, Lobachevskian geometry, and Riemannian geometry (Bonola, 1955). Different geometries are more or less useful for depicting natural phenomena depending on what we are trying to model. However, Einstein showed us that choosing a particular geometry to represent nature is inherently a matter of convention. Ancient natural philosophers such as Archimedes and Aristotle did not see a distinction between geometry and physical space. We are also aware that there always seem to be exceptions to our physical *laws*. For instance, Archimedes likely would have been surprised to learn that not all liquids combine by simple addition: e.g., one cup of water combined with one cup of alcohol yields less than 2 cups of liquid. Archimedes on the other hand thinks that mathematical demonstrations can prove empirical facts. This is a point of departure for Archimedes and it is revealing about Archimedes concept of scientific explanation. In the case of the law of the lever, for example, Archimedes takes the *empirical* fact of weights balancing to be proved when he mathematically proves that two rectangles are equal when they are in the proportionality: BASE1 : base2 :: height2 : HEIGHT1. Archimedes' belief that he has thus mathematically *proven* an empirical fact implies a belief that the basic structure of nature could not be otherwise and that nature is inherently mathematical.

For another example of an ancient natural philosopher who applies mathematics to the investigation of the empirical sciences we turn to Eratosthenes of Cyrene (275-194 B.C.E.). Eratosthenes applied mathematical propositions to observations to determine physical facts, such as the circumference of the Earth. Eratosthenes also reveals an advance in the application of mathematics in the investigation of nature by explicitly treating physical objects as mathematical objects. Eratosthenes, to whom Archimedes sent the *Method*, seems to have studied mathematics and nature in a manner similar to Archimedes. Among other advances, Eratosthenes is credited with being the first person to divide the globe along latitudinal and longitudinal lines (Lloyd, 1973, p. 49). This was an important step in aiding navigation or at least map-making.[66] More famously, Eratosthenes conceived of a way to measure the circumference of the Earth using geometrical propositions.

It was known that in the town of Syene (contemporary Aswan in southern Egypt), the bottom of a deep well was only directly illuminated by the Sun one day a year. This was only possible because the Sun was directly overhead—a vertical rod would cast no discernable shadow. Syene was very near the Tropic of Cancer and the day in question was the Summer Solstice. In the town of Alexandria, which is nearly directly north of Syene, Eratosthenes set up a vertical rod and measured the angle the sunlight made with the rod by measuring the length of the shadow cast at noon on the summer solstice. Eratosthenes assumed that the distance between Syene and Alexandria was negligible compared with the distance between the Earth and sun. This assumption allowed him to consider the rays of sunlight hitting the two towns to be traveling in parallel lines. The angle at which the sunlight hit the top of the vertical rod could be calculated using the height of the rod and the length of the rod's shadow on the ground. Eratosthenes calculated this to be 1/50th of a circle. He further knew by laws of parallel lines that the angle the sunlight made with the rod had to be the same angle between the two radii of the Earth, one terminating in Alexandria, the other in Syene. Hence, multiplying the distance between Alexandria and Syene by 50 gives the circumference of the Earth. Eratosthenes calculated that the circumference of the Earth is roughly 5,000 stades.

[66] Ptolemy greatly expanded this application of geometry to problems of navigation by coming up with a method for measuring celestial angles. Ptolemy's innovation enabled one to calculate their latitude. The problem of determining one's longitude at sea would not be fully resolved until the invention of the portable spring loaded clock in the 18th century.

Although the precise length of a stade is not known, Boyer (1991) claims it was about 1/10th of a mile. If this is accurate, or close to accurate, then multiplying the distance between the towns, 5000 stadia by 50, gives 250,000 stadia or about 25,000 miles, which is remarkably close to NASA's measurement of 24,860 miles (Dutch, 2004).

These examples from Eratosthenes are relevant because they reveal an advance in applying mathematics to nature—they show deliberate abstracting of physical objects to make them fit with the mathematical propositions. Measuring anything involves some kind of mathematical thinking; [67] hence, the blanket statement that someone applied mathematics to nature is not inherently remarkable. Eratosthenes application, on the other hand, is more sophisticated, for instance, when he invents "mathematical fictions" in order to apply mathematical theorems to the empirical world. He abstracts the Earth and Sun as points and deliberately treats as parallel all line segments drawn from any spot on Earth to any spot on the Sun. Given the size of the Earth, treating the Earth and Sun this way is counterintuitive; however, is it eminently useful because it allows for physical problems to be solved just as any other geometry problem drawn in the sand. Although it is a less sophisticated incarnation, Eratosthenes is employing the same type of process that is a cornerstone of Modern natural philosophy as exemplified by Galileo and Newton.

[67] For instance, all scales of measurement are either quantitative, e.g. speed, weight, time, or they are qualitative, e.g. Mohs scale of hardness is qualitative but still allows for linear ordering of substances. Substances are ranked by the scratch test—the harder substance will scratch the softer, but not the other way around. Harder substances are ranked higher than softer substances. This allows for limited kinds of ratios of magnitude even though the magnitude cannot be quantified independently from other substances.

Ptolemy (90-168 C.E.) serves as another example of an ancient natural philosopher making mathematical models to comprehend physical phenomena.[68] The first clue about the significance of mathematics in Ptolemy's work comes from the innovations he made within the field of trigonometry in his creation of the Handy Tables for measuring celestial motion.[69] Specifically, Ptolemy used math to measure the relative movements of the celestial bodies in order to make mathematical models to aid map-making and navigation, as well as to contribute to general knowledge. Ptolemy's trigonometrical innovation was a system for measuring and representing relative radial distances between celestial objects, which allowed him to create mathematical models of celestial motion that could be used to predict where a planet would be at a given time in the future which could then be *tested* by comparing the predicted results with actual empirical observations.

Ptolemy goes further than Archimedes and Eratosthenes in using mathematics to produce working models designed to capture complex phenomena. I argue that Ptolemy holds the metaphysical position that the world is inherently mathematical. This is seen, for instance, in *Almagest* I.3, where Ptolemy argues that celestial bodies must be perfect and therefore must move in perfect, regular circular motion. Ptolemy's metaphysical commitment to the mathematical character of nature is further revealed in his later work *Planatery Hypotheses* (*Hypotheseis Ton Planomenon*), in which Ptolemy proposes ideas about the physical structure of the heavens by making his previous models from the

[68] Ptolemy's work is also important to this dissertation because it is his geocentric models of the solar system that Copernicus is arguing against in the 16th century, which influences Galileo's work.
[69] There is an analogy here to Newton's inspiration in devising the calculus in order to carry out his scientific modeling of phenomena. Newton's calculus enables him to measure the area under a curve by introducing the concept of the progression to a mathematical limit.

Almagest into mechanical models (Sambursky, 1962, p.141). The fact that Ptolemy believes his mathematical models capture the physical structure of the heavens indicates his ultimately realist position as well as his metaphysical commitment to the mathematical character of nature. These positions facilitate Ptolemy's belief that his assertions about natural phenomena are justified to the same degree of warrant that the mathematical propositions have themselves. Thus, Ptolemy is also able to use mathematical objects to inform demonstrations about nature. Of course, not all of Ptolemy's arguments are mathematical. It is useful to identify and examine the various kinds of arguments Ptolemy makes in his mathematical modeling of the solar system.

Ptolemy makes non-mathematical as well as mathematical arguments. The non-mathematical arguments include qualitative arguments that are based on intuitions, for instance physical intuitions about the elements, and counterfactual arguments. Ptolemy makes at least three different kinds of mathematical arguments: (i) formal, e.g. geometrical propositions; (ii) quantitative, e.g. numerical measurement; and (iii) qualitative mathematical arguments, e.g. based on the properties of circles. See Figure 3.3.

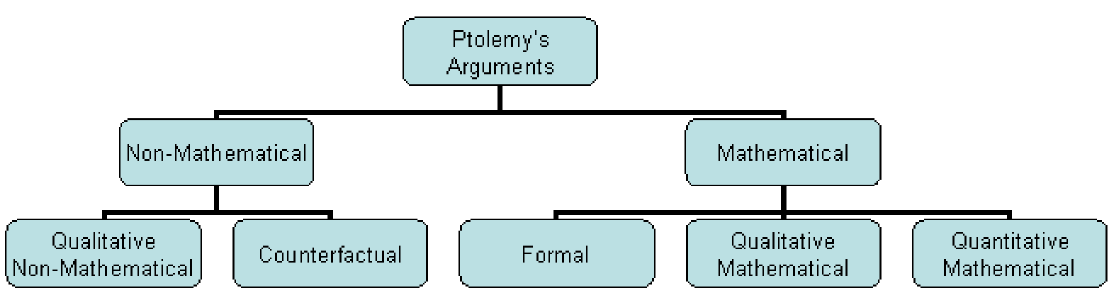

Figure 3.3 These are the kinds of arguments Ptolemy makes

Analyzing each type of argument will help clarify the connection between mathematics and the empirical world in Ptolemy's corpus.

Non-Mathematical Qualitative

An example of a non-mathematical qualitative argument occurs in *The Almagest* I.7, where Ptolemy argues for the immobility of the Earth based on his intuition that it is more likely that light things such as the stars are moving than it is likely that something very heavy such as the Earth is moving. There is an apparent contradiction in the arguments that Ptolemy makes in Book 1 of *The Almagest*, the discussion of which will shed light on Ptolemy's method of demonstration. In 1.7, Ptolemy argues that the Earth does not in any way move locally:

> All those who think it paradoxical that so great a weight as the earth should not waver or move anywhere seem to me to go astray by making their judgment with an eye to their own affects and not to the property of the whole. For it would not still appear so extraordinary to them, I believe, if they stopped to think that the earth's magnitude compared to the whole body surrounding it is in the ratio of a point to it. For thus it seems possible for that which is relatively least to be supported and pressed against from all sides equally and at the same angle by that which is absolutely greatest and homogeneous. (Taliaferro, trans., 1989, p. 11)

Ptolemy argues that the Earth is immobile because it is as a point compared to the whole heavens. I want to call attention to three things in this passage: (i) he analyzes why those arguing for the mobility of the Earth err; they make their judgment based too heavily on their own perspective. Ptolemy rejects the argument that since the Earth is a very large rock, it is likely that it moves just as very heavy boulders are hard to stop moving on their path downward. Ptolemy says this argument relies too much on local phenomena instead of also considering the immensity of the heavens. (ii) Ptolemy explains the intuitive plausibility of the Earth being motionless when one remembers that he has already shown that the Earth is as a point to the heavens.[70] Ptolemy argues that all the rest of the heavens evenly "push" on all sides of the comparatively tiny Earth. (iii) Ptolemy knows that the Earth is "relatively least" compared with the heavens which are "absolutely greatest and homogeneous." Thus, Ptolemy argues that it makes sense that the Earth is motionless because the lesser could not overcome the virtually infinitely greater.

Ptolemy's arguments above appear to be contradicted or at least undermined when he further argues for the immobility of the Earth based on its great weight. Later in *The Almagest* I.7, Ptolemy says:

> For in order for us to grant them what is unnatural in itself, that the lightest and subtlest bodies either do not move at all or no differently from those of contrary nature, while those less light and less subtle bodies in the air are clearly more rapid than all the more terrestrial ones; and to grant that the heaviest and most compact bodies have their proper swift and regular motion, while again these terrestrial bodies are certainly at times not easily moved by anything else—for us to grant these things, they would have to admit that the earth's turning is the swiftest of absolutely all the movements about it because of its making so great a revolution in a short time, so that all those things that were not at rest on the earth would seem to have a movement contrary to it, and never would a cloud be seen to move toward the east nor anything else that flew or was thrown into the air. For the earth would always outstrip them in its eastward motion, so that all other bodies would seem to be left behind and to move towards the west. (Taliaferro, trans., 1989, p. 12)

[70] Ptolemy offers the proof of the claim that the Earth is as a point compared with the heavens in *Almagest* I.6. The gist of the proof is that we do not observe parallax effects when viewing the stars from different places on the Earth. Stellar parallax was not observed until the 19th century.

Ptolemy calls the idea of the heavens not moving while the Earth moves, "unnatural in itself" because he believes the heavens are the "lightest and subtlest bodies."[71] The bodies in the air, such as clouds and lightning, move more rapidly than terrestrial objects do. Ptolemy argues that it does not make sense for the heaviest and most compact body—the Earth—to be spinning with regular and swift motion while the lightest bodies, the heavenly bodies, do not move at all. Ptolemy's argument is based on (i) local phenomena, things in the air (e.g. clouds and lightning bolts are faster moving than earthen things such as rocks) and (ii) the Earth is very heavy and very big, so it is less likely to rotate than the light heavenly bodies. Here Ptolemy is arguing that because the Earth is large and heavy it is less likely for it to be moving than the stars. However, previously Ptolemy argued that it is less likely that the Earth is moving compared with the stars because the Earth is only a point compared with the heavens, which press on it equally from all sides.

Ptolemy further argues that it is the motion of the stars and not the Earth that explains the phenomena by pointing out the "absurdity" of how fast the Earth would have to be rotating in order to "save the appearances" of the celestial bodies making one revolution around the Earth per day. Ptolemy fails to address the speed problem applied to the heavenly bodies; namely, that given their great distance they would have to be

[71] One question is why he thinks the celestial bodies are the lightest. It is likely that Ptolemy would argue that because they are above us and do not fall on us, they must be lighter than anything that could fall on us. If this is the case then it is entirely based on extrapolation from local phenomena, something he scorns in the previous quotation. Of course, there is a sense in which we can only observe local phenomena, e.g. the light from the Moon reaching our eyes, from which we extrapolate the location of the Moon. We have had to construct theories about light and gravity in order to understand why we are sometimes able to see stars that theory tells us are behind the Sun, and so should not be visible—we explain this by saying that light "bends" in gravitational fields.

revolving around the Earth virtually infinitely faster than the Earth would have to be rotating to produce the same observations. This follows from Ptolemy's demonstration that the Earth is only as a point compared to the heavens.

Ptolemy calls the moving Earth hypothesis a "simpler conjecture" but rejects it on the grounds that it does not fit with what we experience. Ptolemy's reasoning may be question begging depending on how he has determined that it is more likely for the stars to revolve around the Earth than it is for the Earth to rotate while the stars remain stationary. If Ptolemy takes our *experience* to be just that the stars are revolving around the Earth, then he is guilty of begging the question because both competing hypotheses would create this same "experience". To avoid begging the question Ptolemy needs some independent reason for justifying the claim that it is more likely for the stars to move than it is for the Earth to move. The question of whether Ptolemy has any independent reason for asserting that stars are light and move in circles is addressed by asking: Why does Ptolemy think it is more likely for the stars to be moving than it is for the Earth to be moving? The answer is that Ptolemy thinks that the idea of the Earth moving while the stars remain motionless is "unnatural" because be believes that the stars are the "lightest and subtlest bodies" and that the Earth is the "heaviest and most compact." His primary reason for believing this is that the stars appear to revolve around the Earth every day. This is circular reasoning.

Ptolemy's problematical thinking is further revealed by his tacit assumption that the motion of the Earth would cause observable phenomena in the air, but that the motion of the heavens would not cause the same phenomena. The Earth being as a point to the whole, if the heavens are able to keep the Earth motionless by pressing down on it, then the incredible speed of the celestial bodies around the Earth should be more than adequate to stir up the air and even to move the Earth. If Ptolemy would argue that this does not occur because the ether is so light it cannot really push the fire or air much, then this would undermine the idea that since they are absolutely greatest, they push the Earth from all sides to keep the Earth immobile.

Non-Mathematical Counterfactual

Ptolemy also makes non-mathematical counterfactual arguments such as for the immobility of the Earth (against those opponents of his theory who posit the "heavens [to be] immobile and the Earth as turning on the same axis from west to east very nearly one revolution a day" [Taliaferro, trans., 1989, p. 12]):

> But it has escaped their notice that, indeed, as far as the appearances of the stars are concerned, nothing would perhaps keep things from being in accordance with this *simpler* conjecture, but that in the light of what happens around us in the air such a notion would seem altogether absurd. (Taliaferro, trans., 1989, p. 12, emphasis added)

The structure of the argument that the Earth cannot be moving that Ptolemy is referring to in this quotation is counterfactual: if the Earth were rotating then we would expect to observe certain counterfactual phenomena such as that clouds would never be seen to move toward the east because the Earth would always be moving faster in the eastward direction, and projectiles and other objects moving in the air would also be dramatically affected by the great speed of the Earth's rotation. In other words: we do not observe certain phenomena; therefore, the Earth cannot be spinning. The basic structure of the arguments tends to be that if the alternate hypothesis were correct, we would observe certain phenomena (x,y,z); however, we do not observe these effects and therefore, by *modus tollens*, the hypothesis is false. To prove that the Earth is not moving (¬P):

1) Assume P
2) P→(x,y,z) (justified by common sense principles such as the addition of velocities, we ought to feel like we are spinning very fast and there should be strange wind effects and strange cannon trajectories, etc.)
3) ¬(x,y,z) (observational data, we do not observe the expected phenomena)
4) ¬P (*modus tollens* taking (2) and (3))
5) Therefore (1) is false and therefore ¬P, the Earth is not moving (excluded middle)

One could make such a counterfactual argument to try to give independent reason for supposing that the stars are lighter than the Earth. One could argue for the hypothesis that celestial objects are lighter than air and fire based on the observation that the stars do not fall on our heads the way heavy objects do. The counterfactual argument would look like the following: Our common experience is that if something is heavy then, when not impeded it falls toward the center of the Earth. If the stars were heavy then they would fall toward the center of the Earth. The stars do not fall toward the center of the Earth. Therefore, the stars are not heavy. Notice this argument assumes that the stars are not impeded from falling. The lack of discussion about whether or not the stars are heavy but impeded from falling toward the center of the Earth shows that Ptolemy’s arguments for the immobility of the Earth are not what must have convinced him of the fact initially, but rather what he thought made the best demonstrations after having fixed his belief.

As mentioned above, Ptolemy also argues for the immobility of the Earth based on the absence of wind effects he believes would be present if the Earth were moving. Ptolemy believes it less likely that the Earth is moving than it is that the stars are moving, because the Earth would have to be spinning very fast, which is hard to imagine for such a big thing. However, since he argues that the Earth must be as a point to the heavens, a reasonable deduction is that the stars must be moving incredibly fast. Of course, since he assumes these are light, it is more intuitive to Ptolemy that they are moving than that the Earth is moving, even though the stars have to be moving at speeds much, much greater than the incredible speed the Earth would have to be moving

Mathematical Formal

Ptolemy also makes mathematical arguments. The first kind to mention is the formal mathematical argument found throughout the *Almagest.* In fact, the *Almagest* is brimming with geometrical propositions that serve Ptolemy's models. Most of the books of the *Almagest* contain multiple demonstrations in Euclidean geometry; i.e. they rely on Euclidean propositions such as that all right triangles in the same semicircle are equal, or that equal arcs subtend equal angels, etc. Most famously, in Book IV, in his discussion about modeling the Moon's motions, Ptolemy demonstrates that the two different hypotheses for capturing planetary motion—the Eccentric and Epicyclic models—are equivalent. That is, they yield identical predictions and fit the data identically. These demonstrations are the most straightforward mathematically and also the most epistemically warranted arguments because they do not contain empirical content. For this reason they serve as a model for empirical demonstrations, but because they do not contain an empirical component the particular details of Ptolemy's formal geometrical arguments are of the least interest to the question of Ptolemy's empirical demonstrations.

Mathematical Qualitative

Ptolemy makes qualitative arguments that are in a sense mathematical, in the sense that he employs his ideas about the properties of mathematical objects as evidence for what nature is like. Examples of this kind of argument include Ptolemy's claim that circles are appropriate to model the heavens, not because the math is simplest but because the heavens must proceed in the best possible way and circles are the best figure.[72] For example, in The *Almagest* I.3, Ptolemy argues the following:

> that, since the movement of the heavenly bodies ought to be the least impeded and most facile, the circle among plane figures offers the easiest path of motion, and the sphere among solids; likewise that, since of different figures having equal perimeters those having the more angles are the greater, the circle is the greatest of plane figures and the sphere of solid figures, and the heavens are greater than any other body. Moreover, certain physical considerations lead to such a conjecture. For example, the fact that of all bodies the ether has the finest and most homogeneous parts; but the surfaces of homogeneous parts must have homogeneous parts, and only the circle is such among plane figures and the sphere among solids. (Taliaferro, trans., 1989, p. 8)

Ptolemy reveals here that his modeling of the heavens is greatly affected by his metaphysical views about what the heavens must be like, i.e. perfect. Ptolemy is not arguing from the position of using the simplest mathematics to account for the

[72] Although comparing this kind of argument to some of Aristotle's arguments is controversial, the apparent similarity is strong enough to warrant consideration. See discussion of *De Caelo* in chapter 2.

phenomena. Instead, Ptolemy is either, explaining why the heavens necessarily move in circular motion; or, Ptolemy believes he has observed that he heavens move in perfect circular motion and is arguing for why this makes intuitive sense. This reveals that Ptolemy is not merely modeling empirical demonstrations on mathematical demonstrations; Ptolemy is treating the empirical world as having an inherently mathematical structure.

Mathematical Quantitative

Quantitative mathematical arguments can be seen all over The *Almagest*, for instance, where Ptolemy demonstrates the efficacy of his models. These kinds of arguments are mathematical because Ptolemy deduces from the mathematical models observational consequences. These kinds of arguments argue from the position that if the observed phenomena are consistent with the mathematical models, then this fact of consistency is evidence for the verisimilitude of the models.[73]

An example of quantitative demonstration is seen where Ptolemy uses the measurements and periods of planetary motion to calculate the actual size of the heavens in *Planetary Hypotheses.* "In a later book, called *Planetary Hypotheses*, he abandons the purely descriptive attitude of a positivist and propounds some ideas about the possible physical structure and causes governing the planetary system" (Sambursky, 1962, p.141). Ptolemy takes the predictive accuracy of his planetary models as evidence that he has

[73] This is akin to the way that contemporary theoretical physicists argue that consistent or simpler mathematics is strong evidence for the existence of the graviton, multidimensional strings, or the planet Vulcan (which was posited to exist to account for *irregularities* in Mercury's orbit before Einstein's theory of General Relativity gave a more satisfactory account).

captured the *true* motions of the planets—the actual physical distances and sizes of celestial objects and their orbits based on the combination of his models with basic measurements. An example of a measurement that would serve Ptolemy in this kind of physical modeling would be Eratosthenes' measurement of the circumference of the Earth. Thus equipped, Ptolemy postulates a mechanical model of planetary motion that puts the celestial bodies in series of nested gears.

The fact that Ptolemy makes a mechanical model speaks to his commitment to the idea that his mathematical models reveal truths about nature. One way to characterize this commitment is as scientific realism, as opposed to scientific instrumentalism. Scientific realism is the view that, in general, and allowing for errors and approximations, the better a scientific theory fits with the observational data, i.e. allows for accurate predictions, and coheres with other robust theories, the closer that theory is to getting at the true or real nature underlying phenomena. Realist language includes talking about theories getting at the "fabric" of nature. Van Fraassen (1980b) defines scientific realism: "Science aims to give us, in its theories, a literally true story of what the world is like; and acceptance of a scientific theory involves the belief that it is true" (p. 8). Scientific instrumentalism, on the other hand, contends that the move from "good fit with observational data" to claims about what truth about nature the theory is revealing are epistemically unjustifiable. Scientific instrumentalists argue that, because there is no independent way to measure how well a theory represents 'nature' except by how well it fits with the observed phenomena, the realists are unjustified in making additional claims about a theory's fit with nature. Realists argue that, by pretending that the point of scientific theories is not to get at what nature really is, instrumentalists are missing the point of science as well as misunderstanding the motivation of most scientists. Determining which side of the debate Ptolemy is on is controversial. However, explaining the competing evidence locating him on each side will help clarify Ptolemy's understanding of scientific demonstration because if Ptolemy is a realist, then we might take his commitment to mathematical modeling and mathematical parsimony as further evidence that he thinks that nature is inherently mathematical.

Strong evidence for claiming that Ptolemy ultimately takes a realist position comes from his later work titled *Planetary Hypotheses*, in which Ptolemy makes a mechanical model of the heavens (Sambursky, 1962, p. 141). Further evidence supporting the claim that Ptolemy is a realist is the fact that he chooses his starting position for his models based on what he believes is true about the heavens and rejects those ideas which are "unnatural" such as that the Earth moves (e.g. Almagest I.7). By contrast, an instrumentalist would not reject a potential model on the grounds that elements of the model violated beliefs about the structure of the world unless these elements precluded the model from saving the appearances. That this is not Ptolemy's approach argues for his being a realist.

On the other hand, there is also strong evidence to support the claim that Ptolemy's method is instrumentalist. He distinguishes between theoretical and practical philosophy and suggests that the closest we can come to certain knowledge in practical areas is to mathematically model observational data (*Almagest*, I.1). This is indicative of instrumentalism. The most powerful evidence for an instrumentalist interpretation of

Ptolemy's work comes from his demonstration in the *Almagest* of the equivalence of his two different mathematical models of heavenly motion: the Eccentric and Epicyclic. This indicates instrumentalism because by demonstrating that the two different models are equivalent Ptolemy is tacitly acknowledging that there is no independent way to adjudicate between his models other than by how well they fit with the data; since both are identical with regard to the observational data, Ptolemy does not say that one is true or more true of heavenly motion.

The instrumentalist camp also argues that Ptolemy has a methodological preference for the simplest mathematical model that squares with appearances. The instrumentalist claim is that the greatest influence on Ptolemy's models is finding the simplest mathematical model that fits with the data. It is argued that this criterion is what dictated that celestial bodies travel in uniform circular motion in his models and even Ptolemy chooses the Earth as the center of the heavens. Thus, the argument is that Ptolemy is an instrumentalist because he has chosen to build models based more on parsimony than on physical knowledge or physical intuition.

There is further support for the instrumentalist idea that Ptolemy is more concerned with simplicity of theory than he is with physical intuitions. Sambursky (1962) reports that Ptolemy's biggest motivation is the elimination of redundancies and, as far as possible, *ad hoc* additions in his theories, which speaks to simplicity of theory. One example of Ptolemy eliminating redundancy is his assumption that either the Earth is moving or the celestial bodies are moving but not both. In fact, Ptolemy does not seem to consider the possibility that both the Earth and the stars are moving in order to produce the appearances. Giving motion to both in his models would have allowed for the Earth to spin more slowly; the rapid speed of the Earth was one of Ptolemy's reasons for rejecting the hypothesis that the Earth's motion produces the appearances. Although it is easier to imagine two contrary motions producing the immense relative speeds necessary for the solar system models, it is nonetheless redundant to have two motions where one would suffice and so would not be as *simple* and hence, it is unacceptable to Ptolemy. The assumption that only one motion accounts for the appearance of the fixed stars traveling daily around the Earth allows Ptolemy to set up the counterfactual that if it is the Earth's motion that explains the appearances then the Earth must be rotating very rapidly, and hence a super-wind.[74]

There is also evidence that works against the argument that Ptolemy is an instrumentalist based on his preference for parsimony over physical knowledge and intuition. For instance, Ptolemy acknowledges that the hypothesis that the Earth is moving instead of all the celestial bodies moving is a *simpler* hypothesis, but he chooses to put the stars in motion in his model instead of the Earth based on his understanding of the nature of heavenly bodies. This is a realist consideration, not an instrumentalist one. Furthermore, the argument that Ptolemy is an instrumentalist based on his apparent interest in simplicity of theory over physical considerations is missing the point that Ptolemy chooses the simplest mathematical models of the heavens because he believes

[74] Of course, the factor more important than simplicity is that the hypotheses must square with experience. Ptolemy thinks that our experience of not being constantly confronted with a thousand mile per hour wind is strong evidence that the Earth is not moving. This 'experience' is only as persuasive evidence as the intuition about a counterfactual world is supportable. Galileo, for instance, does not deny that we do not feel a thousand mile per hour wind, but instead Galileo uses the idea of relative motion to deny Ptolemy's intuition about the effects we would experience in the opposing cases of celestial or terrestrial motion.

that it is necessary that the actual heavenly bodies must move in the most mathematically simple way possible.[75] Instead of being motivated by wanting to use the simplest mathematical models for the instrumental goal of ease of use, Ptolemy uses the simplest math because of his intuition and metaphysical beliefs about the constitution of the heavens.[76]

In addition to showing that mathematics is used as a model for demonstrations in empirical science the examples of Archimedes, Eratosthenes, and Ptolemy provide a glimpse of the expanded connection between mathematics and empirical science. This is seen, for instance, where Eratosthenes introduces mathematical *fictions* that allow him to treat physical objects as mathematical objects.[77] The expanded application of mathematics in empirical scientific demonstration is also seen where Archimedes relies upon mechanical practice to aid in mathematical discovery and geometrical demonstrations to prove physical properties, such as the law of the lever. Of our cases studies, Ptolemy goes the farthest in creating mathematical models of nature, which he then uses to construct mechanical models.

Despite the continued application of mathematics to the study of the natural world by Archimedes, Eratosthenes, and Ptolemy among others (e.g. Aristarchus), in general, after about the second century B.C.E., mathematics became more segregated from other

[75] cf. Newton's Rule 1 in *Principia,* Book III (p. 398).
[76] It is also the case that the simpler math is more convenient; however, Copernicus argues that the mathematical model is simpler if everything revolves around the Sun. If Ptolemy were an instrumentalist he might have proposed a heliocentric model even though it would have seemed entirely implausible to him.
[77] For example, in Eratosthenes' demonstration of the length of the circumference of the Earth, he treats lines that begin at different places on the Earth and end at the Sun as parallel lines even though he believes that these lines cannot be parallel. Given what we know about the relative sizes of the Earth and Sun and the immense distance from the Earth to the Sun, this *fiction* is an obvious one to make; however, Eratosthenes did not have the information we do, and as a geometer, it was a significant step to begin from an assumption that he believed to be false.

sciences, more specialized as a separate discipline. In the third and second centuries, the study of mathematics expanded to "the exclusion of such subjects as the constitution of matter or the classification of natural substances" (Lloyd, 1973, p. 52). Empirical investigation did not stop; for instance, the 3rd century saw the rise of Epicureanism, which is surely 'about nature' – the point is that Epicurean physics is not even remotely quantitative.[78]

3.3 Decline in Empirical Science and Rise in Developing Technology in the Early Middle Ages

> Because Copernicus began where Ptolemy had stopped many people conclude that there was no science during the intervening centuries. In fact, there was much intense though spasmodic scientific activity, and it played an essential role in preparing the ground for the inception and success of the Copernican Revolution. (Kuhn, 1985, p. 100)

Here Kuhn speaks to the misconception that Greek science was extinguished after the second century B.C.E. and that substantial scientific investigation did not begin again until the sixteenth century, with Copernicus. A less extreme but still oversimplified view is that after its "demise" in the second century B.C.E., natural science was not revived until the reintroduction of Aristotle's logic and Euclid's geometry in the twelfth century. There were several notable counterexamples to these claims: Ptolemy, Galen, Iamblichus, Proclus, Simplicius, and Philoponus, among others.[79] There is nonetheless a

[78] Epicurus is clear that the inquiry into nature is also driven entirely by the desire for tranquility – physical investigation is not an end in itself; and it does not matter to Epicurus what explanation is correct, as long as it is materialist (*Letter to Pythocles*, Inwood and Gerson, trans., 1988, p. 16).

[79] Ptolemy's contributions are discussed above. John Philoponus (c. 490-570 C.E.) is mentioned in chapter 2; we will not go into the details of his work here; however, in support of the position that Philoponus

reason for the misconception that Kuhn addresses. The reason is that there was a sharp decline in empirical scientific investigation during the early Middle Ages (roughly the fifth to early twelfth centuries) from the sort of investigations conducted by the list of authors above. This section attributes this decline, at least in part, to the rise of Christianity in general, and Augustine's teachings in particular. The majority of empirical investigation that remained during this time was strictly in the pursuit of technology. What accessible knowledge there was of Greek science was handed down by the Encyclopedists.

This list of counterexamples above notwithstanding, there are reasons for suggesting the view that there was a conspicuous absence of scientific investigation in the early centuries C.E. Augustine (354-430 C.E.) is an exemplar of the general de-emphasis of the importance of scientific investigation or perhaps of investigating nature at all. The following excerpt from Augustine's *Confessions* criticizes the investigation of empirical sciences, especially Aristotle's concept of scientific knowledge for its own sake.

> In addition to that concupiscence of the flesh present in delight in all the senses and in every pleasure—and its slaves put themselves far from you and perish utterly—by reason of those same bodily senses, there is present in the soul a certain vain and curious desire, cloaked over with the title of knowledge and science, not to take pleasure in the flesh but to acquire new experiences through the flesh . . . . Because of this morbid curiosity, monstrous sights are exhibited in the show places. Because of it, men proceed to search out the secrets of nature, things beyond our end, to know which profits us nothing, and of which men desire nothing but the knowing. (X.35, Ryan, trans., 1960, pp. 264-5)

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actually engaged in empirical scientific investigations Wildberg (2007) claims that, "Although the Aristotelian-Neoplatonic tradition was the source of his intellectual roots and concerns, he was an original thinker who eventually broke with that tradition in many important respects, both substantive and methodological, and cleared part of the way which led to more critical and empirical approaches in the natural sciences" (p. 1).

Augustine demarcates in this passage what it is important to study and natural science suffers for it. Although it is controversial, I take Augustine to be condemning studying empirical science for any reason, except perhaps for than spiritual enlightenment. Augustine's reason for disparaging empirical investigation seems to be that it encourages the inappropriate focus of one's attention on to the senses. My position that Augustine undermines natural scientific investigation follows Lloyd (1973) but contradicts Ryan (1960). Ryan holds that this chapter of *Confessions* should not be taken to mean that Augustine is "opposed to valid and worth-while scientific knowledge" (p. 406 endnote 8 to chapter X.35); Ryan argues, instead, that Augustine is interested in genuine knowledge, not idle curiosity. Ryan's generous interpretation takes Augustine to be condemning the seeking of self-indulgent pleasures and feelings, but not condemning genuine empirical scientific investigation. If this is correct, then Ryan would need to elucidate what Augustine considers to be genuine knowledge, which he does not. Ryan would be going too far to claim that Augustine is interested in the kinds of science that Aristotle and his successors are engaged in. This is clear in the last clause of the quotation where Augustine specifically targets the Aristotelian ideal of scientific knowledge for its own sake.

There is further evidence that supports the position that Augustine largely rejects empirical science. Contrary to Ryan's position, it is more likely that Augustine thinks the valid branches of science are quite different from the traditional areas of natural science; for example, in *Confessions* X.35, Augustine says: "I do not care now to know the courses of the stars" (Ryan, trans., 1960, p. 265). Genuine knowledge to Augustine seems to be applicable only to theological matters and not the empirical world.

If Augustine is interested in science, it is only in the general sense of a reasoned method for demonstrating knowledge and not about learning about the empirical world, except perhaps through divine inspiration. Augustine's undermining of natural philosophy is even more apparent in his *Enchiridion on Faith*:

> . . . it is not necessary to probe into the nature of things, as was done by those whom the Greeks call *physici*; nor need we be in alarm lest the Christian should be ignorant of the force and number of the elements—the motion, and order, and eclipses of the heavenly bodies; the form of the heavens; the species and the natures of animals, plants, stones, fountains, rivers, mountains; about chronology and distances; the signs of coming storms; and a thousand other things which those philosophers either have found out, or think they have found out . . . . It is enough for the Christian to believe that the only cause of all created things, whether heavenly or earthly, whether visible or invisible, is the goodness of the Creator, the one true God; and that nothing exists but Himself that does not derive its existence from Him. (Bk. IX, Shaw, trans., 1961, p. 9-10)

By naming the very empirical sciences that Aristotle and his intellectual heirs pursued, Augustine makes even clearer his position that studying nature is a hindrance to proper learning (by which he means Christian theology).[80] Crombie (1953) shares the view that Augustine disavows natural philosophy; Augustine values nature only as "sacramental and symbolic of spiritual truths" (Crombie, 1953, p. 11).

The decline in interest in the inquiry into nature coincides with a decline in interest in using empirical investigative techniques for epistemic justification. As seen in

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[80] When Greek science was reintroduced in the Latin West, the emphasis on Christianity remained, but the sense of inherent conflict between Christianity and science lessened (in some schools). For instance, Adelard of Bath acknowledges that we must look for the physical causes that the divine artificer has used to understand the creator's creation. See Section 3.4 below.

these excerpts Augustine eschews the pursuits of the empirical sciences as well as the foundational investigative technique of the empirical sciences—using one's senses to collect observational data. Augustine's rational technique of divine revelation for theological understanding largely supplanted Aristotle's idea of "getting one's hands dirty" as a way of learning about nature.

Although Augustine and his followers had a strong dampening impact the prevalence of empirical scientific inquiry, it would not be accurate to say that there was *no* empirical investigation during this time. Owing to the interest in manipulating nature, some empirical investigation occurred even though for the most part it was not 'scientific investigation' in the sense of constructing rigorous demonstrations of knowledge. Many significant inventions came out of this time by trial and error discovery techniques.[81] Although there may have been some interest in the 'why' behind the innovations of the time, for the most part the motivation seems to have been pragmatic development of technology. There was a notable absence of theory building and careful epistemic justification. Searching for technological developments without regard to understanding why things work or justifying one's new knowledge contradicts Aristotle's idea of science as the systematic search for natural causes and first principles, which are not sought for practical application.

[81]Technological innovations included new harnessing techniques and the nailed horseshoe, as well as the reintroduction and sophistication of the watermill and windmill, which led to the development of power-driven machinery. These machines used gears and the crank and included the tap hammer, forge bellows, and wood saws, among others. (Crombie, 1953) Combining these machines allowed for improvements in tools such as the plough, and to industrial complexes such as fulling mills. (Derry and Williams, 1960) (Hero of Alexandria had developed a water pump and perhaps even a steam pump in the 1st century C.E., but these were basically toys, not serious machines, and much was lost in Western Christendom after the fall of Rome.)

What remained of Greek science and learning in the Latin West during the early Middle Ages was handed down by the Latin encyclopedists (Crombie, 1995, p. 30). The *Natural History* of Pliny (23-79 C.E.) is one such example of an encyclopedic work that survived in part and influenced scholarship during the early Middle Ages. Before the Greek and Arab ancient texts were translated into Latin in the twelfth century, Pliny's *Natural History* was the largest known collection of data about nature (Crombie, 1995, p. 30-1). Different disciplines owed their intellectual inheritance to different encyclopedists. For instance, much of the Greek math and logic available in the Latin West during the early Middle Ages survived because of Boethius. Much of what was known about medicine was passed down in versions of Oribasius' summaries of Galen's works, although these remained in Greek and so were not commonly accessible.

The decline in the study of nature was in part due to the rise of Christianity (as seen in the Augustine quotations above). It should also be noted that, to some degree, the contrary is also the case: Christian scholarship helped preserve the Greek and Arabic scholarship that had already been done. The vast majority of what survives from antiquity survived because of monk scribes.[82] Also, Christian scholars were the only scholars in the Latin West during this time and some science writing may have survived just because learned people often learn whatever is available. Nonetheless, passing along scientific data is not the same as carrying out the activity of scientific investigation, which is what we are chronicling here.

[82] Although they only account for a small fraction of the extant ancient texts, there have been some remarkable papyrus finds in the last few centuries which do not owe their persistence to the diligent scribes.

Thus, little progress was made with regard to empirical scientific investigation and scientific explanation during the early Middle Ages. Crombie (1995) claims that a "preoccupation with the magical and astrological properties of natural objects was, with the search for moral symbols, the chief characteristic of the scientific outlook of Western Christendom before the 13th century" (p. 36). Next we examine some of the notable thinkers responsible for changing the character of scientific investigation in the Latin West. The next significant advancement in empirical science came with the translation first of Aristotle's treatises on logic and Euclid's geometry into Latin, closely followed by much more of Aristotle's works as well as the works of other Greek natural philosophers.

3.4 Reintroduction of Greek Science Marks the Beginning of Scholasticism and Becomes the Seed of Modern Science.

Understanding how the reintroduction of Greek science influenced scientific thinking beginning in the twelfth century provides a basis for comprehending how the seventeenth century Scientific Revolution, and specifically Galileo's contribution were formed. Instead of thinking of Galileo as beginning modern science in the seventeenth century, it might be more useful to think of Galileo's contribution as solidifying the most important elements of modern science, which really began to form in the twelfth century when philosophers of the Latin West began combining study of the newly translated ancient scientific texts with the medieval tradition of pragmatic empirical investigation. Supporting the view that Modern science began in the twelfth century, Crombie (1953) characterizes the early development of the Modern scientific method as an attempt to apply ancient mathematical techniques of explanation and demonstration found in the ancient texts newly translated into Latin from Greek and Arabic to the medieval traditions of empirical investigation, tradition of, primarily, trial and error.

The earliest and perhaps most significant texts were the twelfth-century Latin translations of Aristotle's logical treatises and Euclid's geometry. Aristotle's texts explain and Euclid's exemplify a system for rigorously demonstrating knowledge. What the Greeks had invented and passed down was geometrical demonstration, or proof, in which a "particular fact was explained when it could be deduced from general principles which related it to other facts" (Crombie, 1953, p. 3). Twelfth century thinkers, thus equipped, began trying to combine this understanding of rigorous demonstration with the more hands on approach of trial and error observation and manipulation of nature that had developed in the early Middle Ages.[83] The result was the roots of Modern experimental science.

Adelard of Bath (*ca.* 1080—1152), who is sometimes credited with the reintroduction of Greek geometry to the Latin West (Burnett, 1998), provides one example of combining rigorous demonstrations with empirical investigation. In Adelard's philosophical writings, which are in the form of a dialogue between a

[83] As discussed in chapter 2 and as will be discussed at greater length in chapter 4, Aristotle believed in "getting his hands dirty." The point being made here is not that Aristotle completely relied on rational reconstruction at the expense of empirical observation; instead the point is that the trial-and-error manipulation of nature for technology's sake eventually gave rise to "experimental science," in the proper sense of experimentation that involves testing hypotheses by controlling variables in manipulated environments.

philosopher and his nephew, Adelard speaks explicitly about looking for explanations that are natural instead of divine:

> Nephew: " . . . when you see plants rise up from it, to what are you to attribute this unless to the wondrous effect of the wondrous divine will?"
>
> Adelard: "It is indeed the will of the Creator that plants should be born from the earth. But that will is not without reason. To make this clear, I agree that plants are born from earth, but not from pure earth: rather, from mixed earth—in the kind of mixture that contains in each of its parts (those at least which lie open to the senses) all four elements with their qualities." (Burnett, trans., 1998, p. 93)

The quotation first exhibits the kind of explanation common during Adelard's time: namely, that phenomenon *x* (in this case plants growing out of seemingly empty soil) is caused by God. However, this type of account lacks explanatory power for Adelard. He expresses a preference for explanations involving evidence from sense data instead of justification supposedly coming from unseen essences. Adelard's explanation moves toward physical causes determinable by sense and reason. But Adelard's limited understanding of elements means that he, too, is basing much reasoning on the unobservable. Nonetheless, this is an improvement in scientific thinking very similar to the Pre-Socratic philosophers trying to develop explanations based on elements rather than on divine intervention. And similar to the Pre-Socratics, Adelard has limited empirical support for supposing what he does about the elements.

Robert Grosseteste's (c. 1168–1253) work also sheds light on the development of empirical scientific investigation including scientific explanation. Grosseteste was the founder of the Oxford school of thought, and may mark the beginning of the Modern tradition of experimental science. Riedl (1942) emphasizes this idea: "In philosophy Grosseteste represents, and indeed might well be called the founder of, a new tradition, characterized by the blending of philosophy with experimental science" (p.2).[84] Grosseteste is useful for our inquiry here because his work has both Ancient and Modern science qualities. His treatises are methodical and clear illustrations of an attempt to address epistemological problems while developing a rudimentary experimental method. Grosseteste discusses his scientific method, including his experimental method, and tries to give justification for his observational techniques. Moreover, as does ancient Greek science, Grosseteste tries to apply his scientific method by giving demonstrations, many of which are mathematical in character, of his findings.

Pointing out further similarities between Grosseteste's scientific method and ancient Greek science allows us to be explicit about where Grosseteste's innovations reveal departure from previous Middle Ages thinkers. Following Aristotle, Grosseteste's theory of subordinate sciences relates the mathematical sciences to the rest of the natural sciences.[85] Grosseteste distinguishes between science *propter quid* (on account of what: reason) and science *quia* (that is the case: fact). Grosseteste applies this distinction in the investigation of the rainbow: "The consideration of the rainbow belongs both to the student of optics (*perspectivi*) and to the physicist, but the fact ('quid') is the province of the physicist and the reason ('*propter quid*') the province of the student of optics" (*De*

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[84] I agree with the thrust of Riedl's claim; however, he is being either too generous or too imprecise when he implies that "experimental science" already existed and Grosseteste was merely incorporating it.

[85] Recall Aristotle's distinction between knowing *why* something happens versus knowing *that* something is the case. See chapter 2.

Iride, Crombie, trans., 1953, p. 117). This is the same distinction that Aristotle makes in the *Posterior Analytics* (79a1-13).

Grosseteste on the Rainbow

Having examined Aristotle's treatment of the rainbow (see chapter 2), examining Grosseteste's explanation of the rainbow illustrates where Grosseteste departs from Aristotle and further, illustrates the extent to which Grosseteste's concept of scientific demonstration is a precursor to Galileo's concept of scientific demonstration. Claims that Galileo invented the concept of empirical experiments (as opposed to thought experiments, which date back at least as far as Aristotle), ignore the fact that Grosseteste worked with a rudimentary experimental method.[86] Unlike his early Middle Ages predecessors, Grosseteste was concerned with epistemic justification: he offered critical analysis of his method for collecting empirical evidence and he was concerned with giving scientific demonstrations. These mark Grosseteste's kind of inquiry as empirical *science*, which is different from the empirical pursuit for new technology.

We are less concerned with Grosseteste's findings about the rainbow than we are with his methods of discovery and justification. Discussing where Grosseteste errs as well as succeeds is informative of his method. Grosseteste earns the label 'empiricist' because of his commitment to the idea that scientific theories must be tested by experiments; it is an explicit part of his method that theories that are contradicted by experimentation must be abandoned (Crombie, 1953, p. 124). However, this does not

[86] See discussion in chapter 1 of common and often misleading accounts in the literature of Galileo's contribution to the Scientific Revolution.

mean that Grosseteste had great experimental technique. The following excerpt from Grosseteste's discussion of optics reveals mistakes due to inadequate sampling and from over-reliance on his physical intuitions/metaphysical beliefs about the orderliness of nature:

> That the size of the angle in the refraction of a ray may be determined in this way, is shown us by experiments similar to those by which we discovered that the reflection of a ray upon a mirror takes place at an angle equal to the angle of incidence. And this same point has been made clear to us by the principle of natural philosophy that 'every operation of nature takes place in the most perfect, orderly, briefest and best way that is possible'. (Crombie, trans., 1953, p. 123-4)

Grosseteste's understanding of and his commitment to the metaphysical principle that nature is orderly led to his thinking that paths in nature, such as the path of light, would trace equal lines and divide angles equally, etc., which yields an incorrect account of refraction. Crombie (1953) points out that Grosseteste could have avoided coming to a false conclusion about refraction had he spent more time following his avowed method of collecting empirical data:

> Very simple experiments could have shown Grosseteste that his quantitative law of refraction was not correct. He was, in fact, primarily a methodologist rather than an experimentalist, and also, perhaps, he was too much obsessed with the principle of economy, according to which he believed *lux* [light] to behave, and with the alleged similarity between refraction and reflection, to arrive at a correct understanding of the problem. (p. 124)

Crombie also identifies the source of Grosseteste's error as his over-reliance on metaphysical commitments, such as the principle of economy.[87]

The criticism, that Grosseteste's metaphysics led him astray is too vague. One might assume that one's metaphysics are a source of error primarily when they are unknown to the holder of them. However, Grosseteste's erroneous demonstration of refraction gives us an example of someone who is aware of and purposely using his metaphysical views to inform his empirical science explanation. Because everyone has metaphysical views, conscious and unconscious, the fact of their existence in a scientist cannot be the problem. What Grosseteste does is to rely, not only on the metaphysical principle that nature is orderly, but also on his assumed ability to correctly apply this principle to specific cases, such as to the path of light. Where Grosseteste goes wrong then is in his inference from the principle of orderliness to the conclusion that light refracts just as it reflects, where the angle of incidence equals the angle of reflection. Thus, a more explicit critique of Grosseteste error, rather than simply claiming that his metaphysics led him astray, is to recognize that in determining his law of refraction he does not adequately empirically test his inference, i.e. the hypothesis that light will bend a certain way because of the orderliness of nature.

Grosseteste's shortcomings as an experimentalist notwithstanding, his explicit discussion of his method for evaluating and constructing scientific explanations is illustrative of his innovations to scientific inquiry. When Grosseteste argues against

[87] The general error of overvaluing metaphysical commitments is not new with Grosseteste, nor does it end with him. Francis Bacon will warn against this problem 400 years later in *The New Organon*. Bacon calls the causes of misunderstanding natural processes because of the false ideas that have seeped into our minds from previous philosophies, "Idols of the Theater."

previous explanations of the rainbow, he uses mathematics, experimental observations, and his metaphysical ideas about the perfection and parsimony of nature.

> Nor can a rainbow be produced by the reflection of the rays of the sun from the convexity of mist descending from the cloud, as from a convex mirror, in such a way that the concavity of the cloud may receive the reflected rays and thus a rainbow appear, because if that were so the shape of all rainbows would not be an arc, and it would happen that in proportion as the sun was higher so would the rainbow be bigger and higher, and in proportion as the sun was lower so would the rainbow be smaller, of which the contrary is manifest to the senses. (*De Iride*, Crombie, trans., 1953, p. 126)

Based on what he thinks is the case about refraction, reflection, and convex mirrors, which, comes from his, albeit limited, experimentation, Grosseteste argues that the rainbow could not be produced by reflection. Having determined that other explanations for the rainbow are insufficient to produce the observed phenomena, Grosseteste infers that his account is the correct one because it accounts for the phenomena.

Grosseteste's reasoning process in the case of the rainbow is indicative of his concept of 'experimental science'. First, Grosseteste determines, supposedly by experimental observations, that reflection in convex mirrors could produce phenomena such as the rainbow; from this, Grosseteste induces that there must be a similar process occurring in the sky that produces the rainbow. He determines that refraction in convex objects produces this effect. He decides that the light from the Sun is refracting in "convex clouds": "Therefore the rainbow must be produced by the refraction of rays of the Sun in the mist of a convex cloud. For I hold that the exterior of a cloud is convex and the interior of it is concave, as is clear from the nature of light and heavy" (Crombie, trans., 1953, p. 126).

Grosseteste takes it for granted that the common understanding of the "light and heavy" will make it obvious to his audience why clouds must have the shape that they do, but this is not obvious. If he is relying on Aristotle's idea that heavy objects fall faster than light objects, then Grosseteste might be thinking that as air becomes heavier (i.e. combined with more water), it will begin to move downward and, as it does, the heavier portions will move down faster, creating a curved shape, hence the concavity and convexity of clouds. Of course Grosseteste is mistaken about the shape of clouds and what exactly is the refracting surface; nonetheless, his explanation is closer to our contemporary understanding of the rainbow than previous explanations are—i.e., that rainbows require both refraction and reflection, and curved refractive surfaces, are all necessary components of our contemporary understanding of the rainbow.

Grosseteste's work has similarities with Aristotle's concept of scientific explanation in that he considers previous and competing accounts, uses mathematical arguments to show impossibilities, and relies heavily on the regularity of nature as well as the intuition that natural phenomena are readily knowable to us. Grosseteste's work also exhibits similarities with Galileo's approach to scientific investigation in that he at least tries to perform empirical experiments and makes inductive arguments for his theories based on specific experimental observations. In spite of his failure to consistently follow his own method, he helped to lay the groundwork for further advances in empirical scientific investigation.

Theodoric on the Rainbow

Theodoric (or Dietrich) of Freiberg (c. 1250-1310 C.E.) is another contributor to the development of empirical scientific investigation during this period. His contribution to the rainbow illustrates a greater conceptual ability to consider the relationship between small scale and large scale phenomena as well as greater sensitivity to avoiding errors caused by metaphysical commitments.

Boyer (1987) describes Theodoric's insight about rainbows:

> Never once did the thought seem to have occurred to [Alhazen], or to anyone (with the possible exception of Albertus Magnus) before the fourteenth century, that a globe of water can be thought of, not as a diminutive spherical cloud, but as a magnified raindrop. This was the brilliantly simple idea which came to Theodoric, and with it he coupled an equally simple postulate—that the rainbow is but the aggregate of the effects produced by each individual raindrop, without reference to the properties of the cone or sphere or other figure which as a totality they might resemble. (p. 112)

It would be difficult to say exactly what led Theodoric to this powerful, yet simple insight. However, we may speculate that the basis for Theodoric's idea is to think more analytically (in the more modern sense of breaking phenomena into components) than Aristotle and Grosseteste appear to have been able to. Instead of positing a separate aggregate body that would explain our sensory perceptions of the rainbow, Theodoric figured out how to aggregate the individual components, knowledge of which is easier to devise through experimentation, for instance, with drops of water. One source of the idea might be the need to account for the fact that the rainbow does not change apparent position with a change in the observer's position (as one might expect it to if it were a large scale reflective phenomenon).

Besides revealing a step in the progression in scientific thinking in his explanation of the rainbow, Theodoric is also relevant to our investigation because he discusses his scientific practice in relation to Aristotle's. Moreover, writing about Aristotle's authority, Theodoric expresses a more sophisticated view than is expressed by Galileo's Aristotelian contemporaries.

> We say that one should teach that which the Philosopher [Aristotle] said, for the authority of his philosophic doctrine and for the respect it deserves; and each one should interpret that which is said according to the same Philosopher, that one never should depart from that which is evident from the senses. (Boyer, trans., 1987, p. 113)[88]

Theodoric is concerned about the relative levels of justification for making a scientific assertion. In this quotation Theodoric acknowledges the importance of studying Aristotle's works, but he also asserts that one's observations should trump Aristotle's findings, when there is disagreement between them. Theodoric is implying that past scientific findings, even by the master, should be revisable based on new observational data. Although Aristotle also implies this in the *Posterior Analytics*, in practice Aristotle does not make much room for new observations to revise his theories. Aristotle instead thinks new observations can lead to deeper knowledge, but he does not talk about what new observational data would be sufficient to falsify his theories. Just as Theodoric was not explicit about how he arrived at his insight about explaining the rainbow, he was not

[88] As a testament to his influence, it is worth noting that Theodoric's referring to Aristotle as "the Philosopher" became common practice from the beginning of Scholasticism through Galileo's time.

explicit about his insight about revising theories, nonetheless, this marked advance in evaluating and constructing scientific explanations.

In general, Theodoric's concept of scientific explanation is not fundamentally different from Aristotle's or Grosseteste's; however, he seems to be capable of exercising greater caution about what assumptions he relies on than they do. One source of error for Aristotle and Grosseteste is a tendency to over-supplement their observations with rational reconstruction, which is illustrated by their discussions of the causes of the rainbow. Recall that Aristotle is forced to make unwarranted assertions about the behavior of mist and color dispersion and Grosseteste virtually assumes that refraction will mimic reflection because nature is perfect. It is especially difficult to explain phenomena that cannot be observed directly or close at hand, but this difficulty could be treated as a caution against theorizing beyond one's ability to empirically test hypotheses.[89] It is not clear exactly how Theodoric seems to have avoided this particular pitfall in empirical science. It may be an illusion that Theodoric had a significantly improved method, created by posterity's only preserving his very best work; after all, it would not be surprising if only his best work survived. In any case, his contribution to the explanation of the rainbow and his discussion about the priority of observation over authority, mark advances in late Middle Ages empirical science.

[89] As above, Ptolemy makes mistakes for similar reasons when arguing for the immobility of the Earth. We will see in chapter 4 that Galileo gives up looking for certain kinds of explanations for things that cannot be directly observed. The effect is that there are fewer spheres Galileo considers for scientific investigation, but the expectation is that there will be greater accuracy and certainty within the areas of investigation that are susceptible to Galileo's methods. Further confirmation of the success of Galileo's project is evinced when we see that Galileo's own mistakes come when he slips back into thinking he can rely on his intuition when he argues for the motion of the Earth based on the tides.

Copernicus

Nicolaus Copernicus (1473-1543) also provides an important link between Ancient and Modern science because, although his basic methodology follows Ptolemy's, he constructed a heliocentric model of the solar-system that provided the subject matter for Galileo's most controversial work.

> Aristotle was the last great cosmologist of antiquity, and Ptolemy, who lived almost five centuries after Aristotle, was its last great astronomer. Until after the death of Copernicus in 1543, the writings of these two men dominated the astronomical and cosmological thought of the West. Copernicus seems their immediate heir, for in the thirteen centuries that separate Ptolemy's death from Copernicus' birth no large and enduring modification had been imposed upon their work. (Kuhn, 1985, p. 100)

Although the Scientific Revolution and the Copernican Revolution are often conflated in casual parlance, it is useful to distinguish between these two significant developments in Western thought. Copernicus' *De Revolutionibus Orbium Caelestium* (1543) was the spark that grew into the Copernican Revolution in astronomy and cosmology. Although it took some time to catch on, Copernicus' revolution moved the previously immovable world. Copernicus changed the way people see the Earth in the heavens: for instance, his system requires that the Earth not be the center of the solar system, that it be insignificant in size and incomprehensibly distant from the fixed stars.[90] The Scientific Revolution, on the other hand, is more broadly understood as a shift in our conception of nature: it includes, but is not limited to, the Copernican Revolution. It is helpful to articulate

[90] This is a necessary assumption that Copernicus makes in order to account for the apparent lack of parallax when viewing the fixed stars from the Earth when the Earth is on opposite sides of the sun, e.g. in spring as opposed to fall. Recall that in the Ptolemaic models, Earth is at the center of everything and it may be much closer to the sphere of the fixed stars (so-called because the stars do not move with respect to each other even though in Ptolemy's models they are revolving *en masse* around the Earth very fast).

Copernicus' influence on Galileo Because the Copernican Revolution constitutes a significant step in the Scientific Revolution, and because, in part, it was through trying to demonstrate Copernicus' heliocentric model that Galileo was led to develop his methods of scientific explanation.

To understand Copernicus' influence on Galileo it is useful to understand Copernicus' concept of scientific explanation. Copernicus was motivated by the inconsistencies and *ad hoc* additions to the Ptolemaic solar-system models. In Copernicus' dedicatory letter to Pope Paul III, he explains his dissatisfaction with the then current state of astronomy:

> So I should like your Holiness to know that I was induced to think of a method of computing the motions of the spheres by nothing else than the knowledge that the Mathematicians are inconsistent in these investigations. For, first, the mathematicians are so unsure of the movements of the Sun and Moon that they cannot even explain or observe the constant length of the seasonal year. Secondly, in determining the motions of these and of the other five planets, they use neither the same principles and hypotheses nor the same demonstrations of the apparent motions and revolutions. (Kuhn, trans., 1985, p.138)

The inconsistencies that Copernicus is railing against include the fact that the equant is different for each planet and the fact that there is no discernable pattern or way to predict how many epicycles or speed fluctuations it would take to account for any given planet's motion in Ptolemy's system.

Despite the great difference in appearance of Copernicus' model compared with Ptolemy's, there is a sense in which Copernicus is committed to the same guiding principles that led Ptolemy to formulate his geocentric model. For instance, Copernicus gets rid of the equant not because he disagrees with the constraint that the planets should move in uniform circular motion as Ptolemy believes; on the contrary, it is because he is committed to the idea of regularity that he is more content to move the Earth from the center of the heavens than he is willing to accept a center of uniform motion eccentric to the orbital center. Although moving the Sun to the center of the universe and putting the Earth in motion is contrary to common sense and the knowledge context of Copernicus' time, Copernicus is able to make the other elements (mathematical elements) of his model simpler. Just as Ptolemy was interested in mathematical parsimony, so was Copernicus. Kuhn (1985) supports the hypothesis that Copernicus and Ptolemy have similar methods by claiming that Copernicus modeled *De Revolutionibus* on Ptolemy's *Almagest* (p. 136).

Kuhn (1985) also claims that *De Revolutionibus* was not itself a revolutionary text, but instead that it was revolution-making, i.e. that it led to a revolution in astronomy and cosmology.

> The significance of the *De Revolutionibus* lies, then, less in what it says itself than in what it caused others to say. The book gave rise to a revolution that it had scarcely enunciated. It is a revolution-making rather than a revolutionary text. Such texts are a relatively frequent and extremely significant phenomenon in the development of scientific thought. They may be described as texts that shift the direction in which scientific thought develops; a revolution-making work is at once the culmination of a past tradition and the source of a novel future tradition. (p. 135)

Kuhn's distinction between "revolutionary" and "revolution-making" texts highlights the cumulative nature of revolutions in thought. Kuhn's assertion in this quotation is supported by the fact that *De Revolutionibus* received a very quiet reception in the early years after its publication. This fact may largely be due to *De Revolutionibus'* preface, which was authored by Copernicus's friend Osiander and essentially snuck into the manuscript just prior to publication without Copernicus' knowledge. The preface indicates an instrumentalist position with regard to the heliocentric model of planetary motion. Even if the preface deflected some of the furor expected due to the publication of *De Revolutionibus*, it is remarkable that the suggestion that the Earth moved was not what was the most provocative for Copernicus' colleagues. Gingerich (2004) attempts to identify all of the reactions contemporary to the publication of *De Revolutionibus.* He concludes:

> My Copernican census eventually helped to establish that the majority of sixteenth-century astronomers thought eliminating the equant was Copernicus' big achievement, because it satisfied the ancient aesthetic principle that eternal celestial motions should be uniform and circular or compounded of uniform and circular parts. (p. 55)[91]

The reaction to *De Revolutionibus* that Gingerich suggests may also reflect what Copernicus thought was most revolutionary about his model.

Despite the fact that both Ptolemy and Copernicus have misleading instrumentalist prefaces to their most famous books, both Ptolemy and Copernicus are nonetheless trying to model planetary motion as they believe it actually is; in other words, they are both scientific realists. Ptolemy was first committed to the appearances

[91] The equant is the point around which a celestial body's speed appears to be uniform, i.e. about which angular velocity is constant. The equant is eccentric to the planet's orbit. This eccentricity was troubling but necessary in Ptolemy's system in order to hold on to the metaphysical or mathematical requirement of uniform circular motion, of a kind, while "saving the appearances" that the planets do not move uniformly around the Earth.

that the Earth is motionless and in the center of the heavens either because of sense data to which he then constructed a mathematical model or because he was committed to the idea that the heavens must move in the simplest way mathematically possible, and his system is what seemed the simplest to him. Copernicus was first committed to the idea that the heavens must move in the simplest way mathematically possible and he was able to simplify the math by making the system heliocentric, which led him to believe that the solar system is in fact heliocentric. Some evidence for his realism again comes from his dedication:

> I consider that opinions which are totally incorrect should be avoided. Therefore, since I was thinking to myself what an absurd piece of play-acting it would be reckoned, by those who knew that the judgements of many centuries had reinforced the opinion that the Earth is placed motionless in the middle of the heaven, as though at its centre, if I on the contrary asserted that the Earth moves, I hesitated for a long time whether to bring my treatise *written to demonstrate its motion*, into the light of day. (Duncan, trans., 1976, p. 9, emphasis added)

Copernicus says that the purpose of his book is to "demonstrate" the motion of the Earth. He could have easily tempered this statement in several ways by inserting instrumentalist language about saving the appearances or the usefulness of creating a model that treats the Earth as *if* it were moving. Instead, Copernicus acknowledges the danger of his idea (which would not be an issue if he were only espousing the instrumentalist model) but posits his idea because the contrary opinions are "totally incorrect". Dobrzycki (1991) argues that it is because of Copernicus' strong realist language in the dedication that Osiander felt compelled to insert his strongly instrumentalist preface (p. 61-2).

Adelard, Grosseteste, Theodoric, and Copernicus facilitated a shift from Aristotle's concept of scientific demonstration to Galileo's by combining the early Middle Ages tradition of trial and error investigation for the sake of technology with Aristotle's requirement of demonstrative rigor in scientific explanations. This shift, resulting from the revival of Greek science in the Latin West, laid the groundwork of the Scientific Revolution, of which Galileo was the key figure.

3.5 The Shared Knowledge of Galileo's Time

One question to consider when asking what is revolutionary about a thinker such as Galileo concerns the shared or common knowledge of the time, i.e. to what extent are new ideas products of the knowledge environment as opposed to being spontaneously generated in each thinker? We have seen the oversimplifications that depict Galileo's methodological innovations in science as simply a straightforward rejection of Aristotle's philosophy of science as though the 1900 intervening years had no impact.[92] Wallace (1984) on the other hand, argues that Galileo is deeply rooted in the teachings of his day:

> Galileo's early science, on this accounting, was in essential continuity with that being developed contemporaneously by Jesuit scholastics. Many of the terms and expressions he uses in these notebooks continue to recur in his later manuscripts and published writings, so much so that one may rightfully regard them as the heritage of the Collegio Romano whose elements still survive in the *nuova scienza* [*Two New Sciences*] of 1638. (p. xi)

[92] See discussion in chapter 1.

Another difficulty to accepting the claim that Galileo's innovations were spontaneously created is that there are clear antecedents to the innovations credited to Galileo. Kuhn (1996) argues that scientific revolutions are in part due to the accumulation of knowledge. A second difficulty is that some of Galileo's contemporaries made similar breakthroughs, although none as great as Galileo's.

One of Galileo's contemporaries who did similar scientific work, including work on projectile motion, was Thomas Harriot. Büttner *et al.* (2002) claim that there is extraordinary similarity between Harriot's work and Galileo's even though there is strong reason to believe the two were never in contact, even through acquaintances. Büttner *et al.* (2002) say this about Harriot:

> . . . a scholar contemporary to Galileo pursued experiments with falling bodies and discovered the law of fall as well as the parabolic shape of the projectile trajectory, that he found the law of the inclined plane, directed the newly invented telescope to the heavens and discovered the mountains on the moon, observed the moons of the planet Jupiter and the sunspots, that he calculated the orbits of heavenly bodies using methods and data of Kepler with whom he corresponded, and that he composed extensive notes dealing with all these issues. (p. 4)

The resemblance between Galileo and Harriot's areas of investigation is striking. It seems incredible that Harriot receives none of the credit for these discoveries and is only rarely mentioned in the history of science, until one learns that Harriot never published a single line from his extensive notes.

One hypothesis about how history progresses claims that new ideas are almost exclusively the products of the time and place in which they occur. A competing hypothesis claims that history is advanced most significantly by the unique ideas of individuals who might have had similar impacts even under different circumstances. The story of Harriot would seem to lend weight to the first hypothesis. Büttner *et al.* (2002) take this claim significantly farther by arguing for the interrelatedness of shared ideas among scholars of the same time even when there is no apparent contact among them.

> Historians who attempt to understand the spreading of these new theories in seventeenth century Europe are confronted with a puzzle. The treatises of this time, as they were written by natural philosophers such as Galileo, Descartes, Baliani, or Harriot, show a great variation with regard to the phenomena considered, the basic axioms, or the deductive organization. Nevertheless, these treatises also show a number of peculiar common features that cannot be explained by their shared starting point in the core assumptions of Aristotelian theory rooted in intuitive physics. (p. 11)

The shared knowledge consists of more than the explicit foundation of a given system, such as Aristotle's philosophy of science. Instead the landscape is imperceptibly altered by each generation, and so it seems as though breakthroughs are erupting spontaneously, while in fact they are the result of the accumulation of previously unrecognized nuances.

The point of this chapter has been to examine some of the small changes, not always recognized, that prepared the context for Galileo's work. For instance, we saw that Greek thinkers after Aristotle such as Archimedes, Eratosthenes, and Ptolemy subtly extended the applicability of mathematics in the empirical sciences. In the early Middle Ages there was a decline in empirical scientific investigation in the Aristotelian tradition but the unscientific, pragmatically oriented pursuit of developing new technology and ways to manipulate nature flourished. Also during this time the influence of Christianity on scholarship in the Latin West grew substantially. Beginning in the twelfth century, thinkers such as Adelard, Grosseteste, and Theodoric began applying Aristotle's writings to the Middle Ages tradition of developing technology. Finally, we looked at Copernicus's revolution-making work. All of these events had an impact on the landscape that gave rise to Galileo's philosophy of science, including his concept of scientific explanation.

Chapter 4. Galileo's Concept of Scientific Explanation

4.1 Introduction

The first half of this chapter examines Galileo's concept of scientific explanation. The second half explores the metaphysical and methodological underpinnings relied upon by Galileo and where these depart from those of his predecessors. Among the figures of the Scientific Revolution, Galileo exerted the single greatest influence on solidifying a change away from Aristotelian science to what became Modern science. Because science is an inherently social and historical process, it is essential to locate Galileo's work in an historical context to discover and explain his concept of scientific explanation. This chapter will illustrate the most revolutionary of Galileo's scientific achievements, which was to advance a new more practical aim for scientific investigations that is based on experimental observations and that strives to construct predictive mathematical models. He did this, in part, by sacrificing some of the scope of Aristotelian natural science for the intended benefit of increased empirical justification. Whereas for Aristotle the ideal of scientific explanations is giving the final cause of the explanandum, Galileo's scientific explanations aim at the proximate, that is the most immediate, cause of a given phenomenon.[93]

Galileo's interest in pragmatic, useful science is apparent in his effort to make science the search for measuring, modeling, predicting, and in general applying scientific

[93] Although the cause that Galileo thinks scientific explanations should give does not align perfectly with any of Aristotle's four causes, the closes match is Aristotle's efficient cause. See discussion in section 4.3 below.

knowledge to various experiences for the purpose of using that knowledge productively. Though in one sense Galileo narrowed the scope of scientific explanations by eliminating Aristotle's final cause from empirical science, in another sense Galileo also expanded the scope of scientific explanations by addressing the problem of choosing among competing theories, whereas Aristotle seems to have been only interested in explanations of phenomena.

Galileo's philosophy of science manifests itself in his understanding of scientific explanation. Galileo believes he has a proper scientific explanation when he can demonstrate that he has a model that can be used to predict phenomena (e.g. demonstrate what he calls the proximate cause of a phenomenon, such as how bodies float) or provide a mathematical model (e.g. of the times squared law for falling bodies). This marks a fundamental shift from Aristotle's view that scientific knowledge is inherently abstract. Aristotle's view is that if scientific knowledge ever has practical applications it is a matter of coincidence, i.e. accidental to the aim of science.[94]

Galileo's scientific explanations are more directly empirically testable than Aristotle's because Galileo rejects Aristotle's requirement for scientific explanations that they derive from the ultimate first principles, i.e. the broadest explanatory principles of a given phenomenon. Furthermore, Galileo rejects the idea that pursuing Aristotelian final causes adds to scientific understanding. Galileo thinks that scientific investigations should only include those principles and causes that directly aid in modeling, predicting, and manipulating phenomena. All other causes and principles which may be arrived at

[94] See chapter 2.1 – 2.2 for discussion of Aristotle's definition of science.

through rational reconstruction instead of empirical observation and which do not aid in modeling, predicting and manipulation phenomena, Galileo calls "remote causes" and rejects.[95]

Galileo's rejection of the manner in which Aristotle's philosophy of science was applied by the 17th century Aristotelians, which involved more rationalizing and less direct empirical observation, as well as his emphasis on experiments led some to characterize Galileo's departure from Aristotle as moving from the rational to the empirical.[96] It is true that Galileo places a greater emphasis on empirical investigation than 17th century contemporaries who call themselves "Aristotelians" do, but it is a gross oversimplification to conclude that through emphasis on empirical observation he has freed himself from the influence of metaphysical commitments and rationalizations. In fact, insofar as Galileo does employ these elements, he is more like Aristotle than the 17th century Aristotelians are.

4.2 Galileo's Project: To Advance A More Pragmatically Focused Science

Galileo is not only interested in making new scientific discoveries; he is equally preoccupied with trying to ingrain in 17th century Italian science his mathematical and pragmatic *method* for conducting science. For instance, Galileo's aim in the *Dialogue Concerning the Two Chief World Systems* (1632) is not just to promote the acceptance of

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[95] Galileo's rejection of Aristotle's final and formal causes comes from his greater focus on the epistemological problems of generating empirical explanations and theories. Galileo upholds his empirical standards so firmly that he sometimes mistakenly rejects explanations, for instance, that seem to involve "action at a distance" such as Kepler's tidal theory which claims that the Moon causes tidal phenomena.

[96] See Cohen (1960) survey of late 19th and early 20th century Galileo scholarship.

the Copernican view of the threefold motion of the Earth.[97] In the prefatory section, "To The Discerning Reader," Galileo says that the *Dialogue* is meant to rebut the idea that Italian scholars have not taken up the Copernican question. [98] His stated purpose for writing the book is to show the serious way in which scientific matters are discussed in Italy. Since he does not say that the purpose of the book is to convince his audience to adopt Copernicanism, a case can be made that even more important to Galileo than the outcome of the discussion about the Copernican system is the method he tries to put forward for scientific explanation and for establishing scientific theories.

Further evidence supporting the idea that in the *Dialogue* Galileo is as concerned with promoting his scientific method, which relies on experimentally determining proximate causes for the sake of making predictive mathematical models, as he is with promoting Copernicanism, comes from the fact that Galileo was taken by surprise at the Vatican's harsh judgment against him after the *Dialogue's* publication. One theory that accounts for why Galileo was surprised suggests that he did not see the *Dialogue* as contravening the Catholic Church's warning to him in 1616, in which he was told not to hold or support Copernicanism in writing or in speech. If this theory is correct, then the subject matter was secondary to Galileo's aim in showing the appropriate method of scientific demonstration.

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[97] Besides the Copernican system, the other competing world system that Galileo is writing about in the *Dialogue* is the Brahe model, which replaced the Ptolemaic system. In the Brahe model the other planets revolve around the Sun while the Sun revolves around the Earth, which remains motionless in the center of the universe.
[98] In fact, Galileo argues that Copernicus' third motion, which usually refers to Copernicus' postulation of an annual rotation of the poles, is not necessary to explain the observable phenomena, in this case, the tides.

There are competing theories about Galileo's intentions behind the *Dialogue*. For instance, he might have thought he was being sufficiently sly in his writing to cover his intention of defending Copernicanism; or he might have thought that the election of Barberini as Urban VIII made him safe from the Church because Barberini had been a friend and patron; or Galileo might have thought that his arguments would have convinced the Church to change their anti-Copernican stance. Or perhaps Galileo was most interested in propagating a new scientific method, but to show its efficacy he used it to demonstrate Copernicanism's verisimilitude, because Galileo's thought his method was likely to provide more robust support for Copernicanism than previous methods.

There is further evidence that unlike Aristotle, Galileo thinks of practical application as the primary aim of scientific investigation. For instance, Galileo puts great effort into inventions such as his Bilancetta, the military compass, and the improvements he made to the telescope. In *La Bilancetta* (*The Little Balance*, 1586), Galileo gives careful instructions for the construction of the balance that gives the proportions of two metals in an alloy. He gives tips for how to count the number of turns of the fine wire using the feel of touching the coil with a thumbnail and listening for the sound the thumbnail makes when dragging across the coils. This shows that Galileo thinks that one needs to be able to make precise measurements in order to discover genuine physical laws. In other words, the practicality is a prerequisite for doing science, not a consequence of it. He points out that the principles of his balance are proved in Archimedes, but Galileo does not take pains to demonstrate them.

Further evidence that this was not merely an academic exercise for Galileo is the fact that he wrote *La Bilancetta* in Italian instead of Latin, which made it accessible to the general public. Galileo also wrote *On Floating Bodies* (1612), in Italian, which was his first major published work that illustrated a developed form of his scientific method. This was Galileo's best-selling book in his lifetime. He published exclusively in Italian from this point on, which was unusual for scholars. Although it was not uncommon at this time in Italy to use the dialogue format, as it had been used since Plato, the fact that Galileo's most advanced works—*Dialogue* and *Two New Sciences*—are dialogues may be further evidence that he was interested in conveying the method of investigation because this way he could engage the general population instead of scholars only. Though it may be the case that the dialogue format was used in *Dialogue* to comply with the Vatican's injunction not to promote Copernicanism, this rationale would not apply to *Two New Sciences*, because it does not take up the question of Copernicanism. In fact, as Galileo's final publication, and hence presumably reflective of his most refined understanding of scientific method, *Two New Sciences* further illustrates this shift in the focus of science because it is a treatise about the strength of materials and the motions of bodies, especially falling bodies, all of which have practical applications from metal working to artillery. Instead of trying to find the essences of materials, Galileo seeks to understand attributes that affect their uses.

Further evidence of Galileo's interest in scientific investigation for usefulness comes from his significant efforts to make money from his extracurricular scientific work.[99] For instance, Galileo's desire to discover and apply scientific findings for the purpose of making money, which is suggestive of the shift Galileo makes in science, is illustrated by his efforts to win the prize for solving the longitude problem. Vying to solve the longitude problem was not restricted to natural philosophers—sailors, instrument makers, clock makers, and hobbyists were among those who attempted to solve the problem. Nor was it the case that Aristotelian astronomers were necessarily uninterested in solving the problem. Rather, the difference between the Aristotelians and Galileo is in their approaches or attitudes toward scientific investigation: the Aristotelians pursued the principles of celestial movement for its own sake, for highest knowledge, and then perhaps looked to apply these principles to aid navigation, whereas I claim that Galileo saw solving problems such as the longitude problem as the primary point of scientific investigation.[100]

4.3 The Shift from Searching for Remote Causes to Searching for Proximate Causes

This new scientific approach, however, was not without criticism. For instance, in October 1638 Descartes wrote to Mersenne about the shortcomings in Galileo's recently published *Two New Sciences*.

[99] Pursuing scientific knowledge for the sake of making money was very different from Aristotle's conception of science. An earlier example of this use of science is provided by Leonardo da Vinci (1452-1519), in the form of a letter he wrote to Ludovico Sforza, in 1481, in which Leonardo gives his resume for making war machines and begs for work. See Kemp (1989).

[100] In 1636, Galileo submitted, to the States General of the Netherlands, his proposal for a method of determining longitude at sea using eclipses of the Medicean Stars (the then-visible moons of Jupiter). He later received a gold chain worth 500 Florins for his efforts. This approach was still being attempted in the 18th century.

> But [Galileo] seems to me very faulty in continually making digressions and never stopping to explain completely any matter, which shows that he has not examined things in order, and that without having considered the first causes of nature he has only sought the reasons of some particular effects, and thus he has built without foundation (Drake, 1978, pp. 387-8).

Descartes' primary problem with Galileo is his disregard for "first causes." Descartes argued that scientific explanations must begin with the first principles of a science and then proceed "in order" from these principles to the phenomena being explained. Galileo on the other hand, by not worrying about remote principles, such as dynamical principles of motion, or indeed God (for Descartes: cf. *The World*, *Principles of Philosophy*) is free to model phenomena without having to make competing dynamical principles cohere, which, as described in chapter 2, is a substantive problem for Aristotle (e.g. violent motion).

Caution needs to be taken to avoid over-simplifying the difference between Galileo and his detractors: Galileo's innovation of rejecting Aristotelian causation in explanations is not absolute; it is wrong to suppose that Galileo's contemporaries were only interested in causes, especially remote causes (e.g. 'final' and 'formal' causes), and that Galileo had no use for the concept of causation. Although it is true that Galileo rejects the notion that scientific knowledge is knowledge about the most *remote* and least useful causes or principles, Galileo is still interested in finding the causes *proximate* to phenomena under investigation. In order to explain the difference and discuss the objections, the definition of the kind of 'cause' that Galileo does find useful in science is given below.

In the *Discourse on Floating Bodies* (1612) Galileo discusses causation and gives the following implicit definition of the kind of cause (*cagione*) he employs in scientific explanations: "cause which, being present, the effect is there, and being removed, the effect is taken away" (Drake, trans., 1981, p. 130). Galileo's definition implies two compliance tests for identifying the kind of causation he thinks is relevant to scientific explanations and theories. If *x* and *y* are the potential cause and effect respectively that are being tested, then: (i) if *x* is present, then is *y* also present? And, (ii) if *x* is not present, then is *y* also not present? One immediate problem, however, with this definition is that it cannot distinguish between the cause and the effect. In the case where *x* is the only cause of *y* and they are always present together, i.e. if it is never the case that *y* is present while *x* is not, it is not possible to discern the direction of causality. In other words, this definition does not necessarily answer the question of whether *x* is the cause of *y* or *y* is the cause of *x*. Before we address this problem we need to explain how this definition provides a context in which to understand just what proximate versus remote causes are and how the distinction between them helps clarify what is different about Galileo's project.

This definition of causation shows the difference between Galileo's and Aristotle's understandings of causation in science. Galileo is explicit about why he thinks his concept of causation is the one appropriate to scientific explanations:

> Indeed, the immediate cause is its being less heavy than water, and the predominance of air is the cause of less heaviness, so that whoever offers as the cause the predominance of this element adduces the cause of the cause, not the proximate and immediate cause. Now, who does not know

> that the true cause is the immediate cause, and not the mediate? (Drake, trans., 1981, p. 70)

This quotation shows that Drake's assertion that Galileo rejects causal explanation is not accurate. There remains a place for causal explanations in Galileo's science, but his position is that it is the immediate or proximate causes that are relevant to scientific explanations and that the remote causes he accuses the Aristotelians of pursuing have no place in empirical science.

This is demonstrated by Galileo's argument that the cause of a body's sinking is because of its having a greater specific heaviness (density) than the specific heaviness of water. In other words, objects sink when they displace an amount of water that weighs less than the object doing the displacing. This explanation fits with his definition of causation. When greater specific heaviness is present, objects sink. When greater specific heaviness is not present objects do not sink, i.e. they float.

This explanation for why bodies float is a case, however, where Galileo's definition does not distinguish the cause from the effect, since the presence of sinking is necessary and sufficient for the presence of greater specific heaviness of the sinking object. However, in this case the definitional problem does not hinder Galileo because it is not an open question whether something sinks because it is dense or is dense because it sinks. The latter would suggest that certain things are made denser by sinking—but this is nonsensical because if they were not already denser than water they would not sink and could not then be made denser by sinking. Hence, this example illustrates both the problem with Galileo's definition of not being able to distinguish cause from effect, and

Galileo's (albeit unsatisfying) treatment of the problem—he seems to assume that it is not a problem at all because the direction of causality will always be intuitively obvious.

This example from *Floating Bodies* captures the significance of the shift in science. Galileo's critics argue that by looking for only the *proximate* cause, such as specific heaviness in the cause of floating, and not looking further, Galileo has not actually revealed the *cause* of floating in an explanatory sense. In Aristotelian terms, for something to be a scientific explanation it must employ the broadest explanatory principle possible for that science. For instance, the remote or ultimate Aristotelian cause that explains human mortality comes from the fact that we are animals. Although Galileo does not address this example specifically, by analogy Galileo would be looking for quantifiable phenomena that could predict mortality, such as the time it takes for someone to die from air deprivation (hypoxia) or exsanguination. Galileo argues that by searching for the ultimate cause of why certain things are denser than others, the Aristotelians increase error without aiding scientific knowledge. Galileo is explicit about the problem with Aristotle's insistence that scientific explanations should consist of ultimate causes, or in Aristotle's terminology final and formal causes:

> Besides, he who alleges heaviness brings forth a cause well known to our senses, because we can very easily ascertain whether ebony, for example, or fir, is heavier or less heavy than water; but who will make manifest to us whether the element of earth, or that of air, has predominance in them? (Drake, trans., 1981, p. 72)

The Aristotelians are interested in whether something floats because they think this observation will get them closer to knowing *why* it floats, especially the final cause of why it floats. Galileo argues that observing floating cannot generate the answer the Aristotelians are looking for. The Aristotelians are primarily interested in which things float only insofar as it illuminates deep truths about bodies in general. Galileo is interested in which things float because being able to use knowledge about floating facilitates more control and use of nature.

Galileo further argues that it is neither helpful nor useful to say that something floats because it has more air or less earth in it, because this information can only be reasoned to after the fact, i.e. after having already observed whether or not the object floats. In contrast, with Galileo's emphasis on the proximate cause of floating, which he identifies as specific heaviness (i.e. density), one can weigh objects and make predictions about whether or not they will float. Succinctly showing the circularity of the Aristotelians' method Galileo says:

> For he knows it floats when he knows air has predominance, but he does not know that air predominates except when he sees it float, and therefore he does not know that it floats except after having seen it float. (Drake, trans., 1981, p. 72)

However, Galileo does not reject all elemental explanations. For instance, he would not object to someone's developing a better test for density. However, the conflict between Galileo and the Aristotelians would remain because the new test would only indicate *if* something will float and not *why* it floats in an Aristotelian sense; i.e. the new test would still not reveal why *density* is correlated with floating (as opposed to some other property) any more than the floating test does. The Aristotelians would make the same inference from density to ratios of elements such as earth and water and Galileo would still argue that there is no value in rationally reconstructing causes that are useless for predicting and manipulating phenomena.

Galileo's work on free fall provides another example of the differences between Galileo's and the Aristotelians' concepts of scientific explanation. Instead of searching for the ultimate cause of falling, such as would be needed to generate an explanation that satisfies Aristotle's account, Galileo is interested more in characterizing how bodies fall, i.e. the rate of acceleration of bodies. Galileo is concerned that he needs to explain why there is a small gap in the fit between his theory and experience, which he does with air resistance. The Aristotelians, however, do not worry about the large discrepancy between what was observed at the tower and Aristotle's theory that the rate at which objects fall is proportional to their weights. It appears that compared to the Aristotelians, Galileo is not opposed to more general and reductive accounts if they can be given empirical teeth, but rather objects to simply inventing them out of whole cloth as is the case with the appeal to occult properties. Galileo eschews looking for elemental causes if it is impossible to learn about them, for instance, if they are unknowable given the current state of knowledge and technology, or if they are in principle impossible to know scientifically.

In another example, the case of floating bodies, the Aristotelians have a hard time explaining why a pot filled with water sinks although an empty pot sitting upright floats. They have even greater difficulty explaining why the same empty pot floats or sinks depending on its orientation when placed in water. This is because they do not understand displacement. However, even if they understood the concept of displacement, they would still have thought that floating was susceptible to further explanations than Galileo's 'specific heaviness' by searching for the primary cause of density. Thus, Aristotelians, even when they feel they have found the Aristotelian ultimate cause, cannot use scientific knowledge to predict which items will float. In contrast, Galileo's method provides a model of floating that allows for testing and quantifying. Once confirmed, Galileo can use this knowledge to predict which items will float and to construct better floating things (e.g. only with this understanding of floating could someone think of constructing ships of iron instead of wood).

4.4 Three-Part Method of Generating Scientific Demonstrations

To better understand the differences between the Aristotelian concept of scientific demonstration and Galileo's, it is useful to explicate Galileo's three-part method for generating scientific demonstrations, and hence what constitutes scientific knowledge for Galileo. Galileo tends to use the following schema: (i) lay out all of the reasonable possible theories or explanations for a given phenomenon; (ii) find arguments that discredit, ideally, all but one of the possible explanations; thus, ideally after step (ii) only one of the possible explanations remains; in this case step (iii) is to show how the remaining explanation does in fact reasonably account for the given phenomenon, and to account for any counter-objections or anomalies in the explanation. Galileo judges himself to be successful only when he is satisfied that he has provided the proximate cause of the phenomenon in question. Step (ii), elimination of incorrect explanations, takes of the form of demonstrating that the incorrect explanations do not or, preferably, cannot give the proximate cause of the phenomenon.

Galileo's three-step process seems straightforward; however, it soon becomes clear that there are several pitfalls. For instance, a lot of work is done in step (i) by the criterion of reasonableness; this is a problem because Galileo is not always clear about how he judges reasonableness. For instance, Galileo rejects as completely unreasonable the theory that the tides are caused by the Moon, which leads him into error. Another difficulty occurs when there is not enough information to discredit all but one of the possible explanations. For this less than ideal, but common, case where more than one possibility remains after step (ii), a different third step is required: (iiia) the task then is to explain why one of the explanations is preferable to the others by using certain criteria such as preference for generality or preference for specificity, predictive accuracy, simplicity (i.e. conformity to Ockham's razor), plausibility, *etc*. As will be discussed in the second half of the chapter, one's metaphysics necessarily plays a significant role throughout the scientific process; this is most apparent in this variation of the third step (iiia), where the different properties among theories do not obviously yield a unique solution.

4.5 Two Case Studies: Ashen Light of the Moon and Tidal Theory

Ashen Light of the Moon (Earthshine)

Investigating two specific cases will help illustrate the development of Galileo's scientific method. The first case to be considered is Galileo's explanation of, i.e. his demonstration of the proximate cause of, the ashen (secondary) light of the Moon. In *The Starry Messenger* (*Sidereus Nuncius*) (1610) Galileo demonstrates the cause of the ashen colored, faint light of the Moon or as he calls it, the 'secondary brightness' of the Moon (Finocchiaro, 2008). Contemporary stargazers call this earthshine, a name made possible by Galileo's correct explanation of the phenomenon.[101] Earthshine is the glow visible around the circumference and on the part of the surface of the Moon unilluminated directly by the Sun. This is visible between Last Quarter Moon and First Quarter Moon, i.e. when the Moon is less than half full. Sometimes this is seen merely as the faint outline of the rest of the circumference from the illuminated crescent of the Moon before and after the new Moon. Galileo begins his discussion about the cause of Earthshine by considering the theories previously put forward. In this case his method seems similar to how Aristotle often begins investigations. However, whereas Aristotle deliberately considers what all reputable philosophers have previously said on a subject (See: *Metaphysics* I.3; *Physics* I.2; *Parts of Animals* I.1), Galileo is only incidentally interested in what other philosophers have said insofar as it aids the process of laying out all of the

[101] The name: "Galilean Light of the Moon," should now replace all previous names for this phenomenon.

possible explanations for a given phenomenon.[102] Galileo's demonstration of the correct explanation of the secondary light consists of his first refuting all the false explanations and then explaining how the only remaining possibility does in fact account for the phenomenon.

The initially plausible competing explanations that Galileo deals with include: 1) that earthshine comes from the Moon itself; 2) that the light is a reflection of the light from Venus or the stars; and 3) that the Sun's light penetrates all the way through the Moon. Galileo demonstrates that each of these seemingly plausible theories is incorrect. If the light came from either the stars or the Moon itself, it would be especially apparent during lunar eclipses because at those times the Moon is in the Earth's shadow and therefore cannot be illuminated by the Sun. However, the earthshine phenomenon is not what is observed during lunar eclipses.

Galileo does not think that the light observed during eclipses is this same ashen light—he argues instead it is a different phenomenon altogether. He observed that during an eclipse the light seen on the Moon is "much weaker, somewhat reddish, and almost coppery" (*Messenger*, Van Helden, trans., 1989, p. 54). Galileo claims that, unlike the ashen light, the light during an eclipse moves and is always concentrated near the edge of the arc of Earth's shadow. Galileo implies that these two observations are sufficient to prove that the ashen light is not the same phenomenon as light during an eclipse: "From this we understand with *complete certainty* that this light comes about because of the proximity of the solar rays falling upon some denser region which surrounds the Moon on

[102] Galileo's biographer Vincenzio Viviani claimed Galileo had fewer books and spent less time studying the works of others than most philosophers of the period. (Drake, 1957, p. 240)

all sides" (*Messenger*, Van Helden, trans., 1989, p. 55, emphasis added). It is not clear what Galileo's ground is for asserting that we know this with "complete certainty". Kepler's (correct) theory is that during an eclipse sunlight refracts through Earth's atmosphere and illuminates the Moon. Galileo is certain that his theory is correct, which turns out to be false. Galileo errs because he has not applied his own method. Galileo's lapse here highlights a problem in his own method; namely, that he makes no room for the possibility that new plausible hypotheses may turn up. Despite his great advances elsewhere, Galileo's assumption that his certainty about his assertions is epistemically justified leads him into trouble similar to what Aristotle faces.

For example, Galileo seems to take the phenomenon of light on the Moon during eclipse as evidence that the Moon has an atmosphere. Although the Moon does have a very rare atmosphere, we now take this phenomenon to be evidence of atmospheric filtering and refraction through Earth's atmosphere, just as Kepler described. Despite his false assertion about the cause of the reddish eclipse light, Galileo's claim that the secondary light is not seen during an eclipse is good evidence to reject the theories that claim the ashen light is reflected from the stars or produced by the Moon itself.

Galileo also debunks the theory that earthshine is reflected from Venus by pointing out the geometrical impossibility of light from Venus reaching that part of the surface of the Moon unilluminated by the Sun when Venus is at or near conjunction with the Earth. This would be true at both superior and inferior conjunction.[103] His arguments

[103] Conjunction refers to the apparent alignment of two celestial bodies viewed from Earth. At superior conjunction the Sun is between Venus and the Earth; at inferior conjunction Venus and the Earth are on the same side of the Sun.

are compatible with both the Copernican system he prefers and the Tycho Brahe model, which the Aristotelians had adopted by the early 17^{th} century. The possibility that the ashen light of the Moon is caused by the Sun's light reflected off Venus when at superior conjunction is rejected because it is nonsensical to suppose that the light reflected off Venus could illuminate the Moon by shining through the Sun. Galileo rejects the possibility that reflected light from Venus illuminates the Moon when it is at inferior conjunction because light striking Venus when it is directly in line with the Earth and the Sun would be reflected away from the Moon. See Figures 4.1 and 4.2.

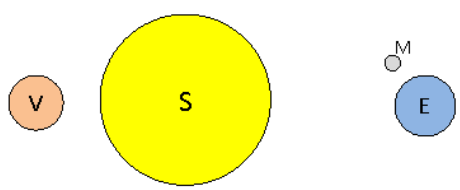

Figure 4.1 Superior Conjunction

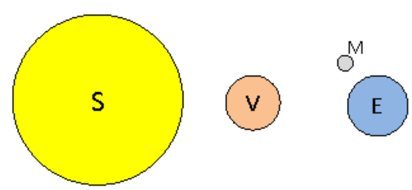

Figure 4.2 Inferior Conjunction

In Figure 4.1 Venus is at superior conjunction with Earth. In Figure 4.2 Venus is at inferior conjunction with Earth. Galileo rightly argues that neither arrangement could allow sunlight reflected off of Venus to illuminate the Moon. Note: The relative sizes of the satellites are roughly correct; however, due to space limitations the Sun is depicted $1/40^{th}$ of its actual size in relation to Earth. The relative distances to the Sun have been greatly compressed; the relative distance between the Earth and Moon has been exaggerated for visual clarity.

Further evidence that light from Venus cannot reach the Earth or Moon during either conjunction is that Venus is not visible to us during these times. Further, Galileo notes that the angular distance between Venus and the Sun never exceeds 60 degrees, which entails that even when not at conjunction, light traveling from Venus could not reach the surface of the Moon illuminated by the ashen light. See Figure 4.3 below; the vertical line shading represents the area of the Moon that could be reached by light traveling from Earth but that could not be reached by light from Venus.

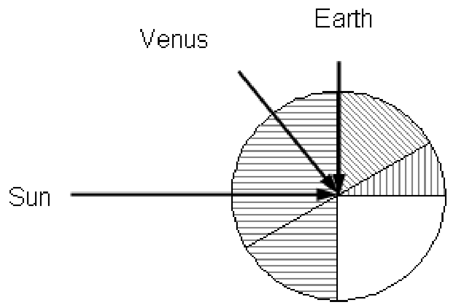

Figure 4.3 depicts the geometric possibility of how Light from the Sun, Venus, and Earth could illuminate the Moon. Bold arrows represent the direction of light traveling from the Sun, Venus, and Earth. Horizontal lines represent sunlight on the Moon. Angled lines represent that part of the Moon that venuslight can reach but sunlight cannot. Vertical lines represent that part of the Moon that earthlight can reach but venuslight cannot.

Figure 4.3 Illumination of the Moon

Galileo goes on to explain how we know that it is not the case that the Sun's light permeates the Moon. Galileo's argument is that if the Sun's light did penetrate the Moon then the secondary light would never be diminished except during lunar eclipses. However, this again is contradicted by the observed phenomena. Galileo points out that the secondary light diminishes as the Moon approaches quadrature.[104]

Although Galileo's conclusion is correct, this represents an example of a problem with his three part demonstrative method because he is too quick to reject this theory. For instance, he does not seem to consider the possibility that the Moon might be made of a semi-translucent material that only deflects a minimal amount of sunlight from a rectilinear path.[105] In this case we would still expect to see the secondary light diminish as the Moon approached quadrature because of the ever-increasing angle formed by our line of vision to the Moon and the path of the light from the Sun to the Moon. This

[104] Quadrature occurs twice per lunar cycle and refers to the midpoints between Full and New Moons; the angle between Sun, Earth and Moon is 90 degrees.
[105] This or a similar idea might have easily occurred to Galileo because of the common, Aristotelian view that the celestial bodies are constituted by the 5th Aristotelian element, quintessence.

oversight of Galileo's may reveal that he had already made up his mind about the idea that the Moon's matter is similar to that of the Earth, a stance which would make it unnecessary to take seriously the translucent Moon theory of secondary light.

We see from Galileo's treatment of competing explanations in the secondary light example, that a potential source of error in Galileo's demonstrative method involves the process of elimination. Since he has explained why the secondary light cannot be coming from the Moon, stars, Sun or other planets, Galileo takes it as necessary that the cause must be the only remaining celestial body—namely the Earth. It is important to note that his demonstration does not end there, with the elimination of the other possibilities. Galileo is not satisfied until he can give a plausible demonstration of how the remaining theory actually accounts for the phenomenon. In the case of earthshine, Galileo takes pains to explain the geometry that makes intelligible the concept of earthshine being reflected light from the Earth. The geometry of the orbits necessitates that the Moon "sees" the Earth in the opposite phase from that in which the Earth "sees" the Moon. Hence, at the time of the new Moon, someone on the Moon would see the full Earth because the Sun is illuminating the entire hemisphere. Conversely, at the full Moon, observers on the Moon would see the new Earth phase. The portion of the Earth being illuminated by the Sun faces away from the Moon, so this sunlight is reflected off the Earth, away from the Moon. The demonstration is complete only after Galileo explains how the secondary light and its variations could be caused by the reflection of sunlight off of the Earth by showing geometrically how the angles of reflection between the Sun, Earth, and Moon could produce the observed phenomena.

In presenting these examples of scientific demonstrations, Galileo gives the impression that the heavy lifting in his scientific demonstrations is done directly by the observable phenomena; however, without discussing it explicitly, equally heavy lifting is done by Galileo's elimination of potential hypotheses as being implausible. It makes sense that implausible theories would be rejected, but Galileo is not explicit about how he judges which hypotheses are implausible. Equally problematic is Galileo's failure to explain how he can be certain that some better hypothesis will not present itself in the future.

Tidal Theory

Galileo's method for demonstrating the cause of the tides is the same as his method for demonstrating the cause of earthshine. First, he considers the possible explanations. Next, he refutes the false accounts. Finally, he demonstrates how the remaining theory does in fact account for the phenomenon being explained. Galileo does not think the alternative tidal theories to his own have merit and so he believes they do not require serious refutation. The primary competing theory is that the tides are moved by attraction to the Moon.[106] Kepler is the leading proponent of this theory in the 17th century, although this view goes back at least to Posidonius in the 1st century B.C.E. Galileo believes he has done away with the plausibility of this theory by calling it "repugnant" to the senses:

[106] Galileo also briefly mentions and dispenses with the theory that the Moon's heat rarefies the water nearest it and the theory that the deepest waters of the ocean cause the tides by moving the less dense shallower waters around (*Dialogue,* Drake, 1981, p. 487).

> "…almost as though the moon and sun were taking part in the production of such effects. But that concept is *completely repugnant* to my mind; for seeing how this movement of the oceans is a local and sensible one, made in an immense bulk of water, I cannot bring myself to give credence to such causes as lights, warm temperatures, predominances of *occult* qualities, and similar idle imaginings. (*Dialogue*, Drake, trans., 1981, p. 516, emphasis added)

Galileo's rejection of the lunar attraction theory seems to be generated by the theory's apparent reliance on pseudo-explanatory occult forces. Galileo is either unaware of or unconvinced by the absence of appeal to occult forces in Kepler's theory. What is repugnant to Galileo's mind is the idea of action at a distance. Galileo is not looking for a better dynamical theory to explain how action at a distance might occur, because he rejects *a priori* the notion that there could be any action at a distance. Thus, any theory that includes action at a distance, regardless of the dynamical account given, does not require disproving. This process of eliminating alternative hypotheses demonstrates the significant role that Galileo's theoretical framework plays in his decisions about what is plausible versus what is unthinkable.

Since Galileo does not seriously consider the competing theories of the tides, Galileo's discussion about the tides hinges on the final step of his method; specifically, demonstrating how the only remaining possible theory properly explains the phenomenon. If Galileo can demonstrate the verisimilitude of his tidal theory, then he will have vindicated the Copernican view that the Earth moves. To do this, Galileo needs to eliminate potential obstacles to his theory, the largest of which are the considerable arguments against the idea that the Earth moves.

Galileo was convinced of the Copernican hypothesis about the motion of the Earth prior to the first time he publically wrote about the tides in 1616.[107] In a letter Galileo wrote to Kepler in 1597, Galileo claims that he has already been an advocate of the Copernican theory for "several" years (Drake, 1970, p. 200). This is also evident from his tidal theory's utter dependence on the postulation of a twofold motion of the Earth, if we assume that his theory had the same basic structure from its inception. This early date of acceptance is important to understanding Galileo's scientific method because it was not until 1609 that Galileo had physical evidence for the Copernican or the Brahe models.[108] It was in late spring or early summer of that year that Galileo learned about the telescope and constructed a model of his own with which he was able to see that at least some heavenly bodies do not revolve around the Earth.

In December of 1609, Galileo used the telescope to determine that Venus has phases consistent with its revolving around the Sun, and inconsistent with the Ptolemaic scheme. This removes an 'anomaly' from the Copernican and Brahe models, since it explains why Venus' apparent brightness does not alter much even though its distance from us varies by a factor of five. Venus having phases explains this phenomenon because brightness varies inversely with distance. So, when Venus is closer to Earth, less of the sunlight reflecting off of Venus reaches Earth, but what does reach Earth is

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[107] In early 1616 Galileo wrote a treatise that presented his tidal theory (in substantively the same form as it appeared in the *Dialogue*, 1632), which Galileo then sent Cardinal Alessandro Orsini (Drake, 1978, p. 252). A few weeks later Galileo was warned by the Inquisition not to support Copernicanism in print.

[108] Tycho Brahe's model largely replaced Ptolemy's in the early part of the 17th century. The Brahe model is a kind of admixture of Ptolemy's and Copernicus' models. Brahe retains the Earth as the center of universe, which is orbited by the Sun, Moon and the fixed stars, as in the Ptolemaic model; however, in Brahe's model the planets orbit around the Sun, as in the Copernican model. And for this reason (i.e. the fact that it makes the Earth stationary), the Brahe model cannot underwrite Galileo's tidal theory – but, Galileo's telescopic evidence is consistent with Brahe and Copernicus.

brighter than what reaches us from Venus when it is further away. When Venus is further away more of its illuminated surface is visible to us. The greater brightness because of greater visible surface area is roughly balanced by the greater distance from Earth.

Galileo's discovery and observations of the 'Medicean Stars', the four largest moons of Jupiter—Io, Europa, Ganymede, and Callisto—also gave compelling evidence (although not everyone was immediately compelled) that there are celestial objects that do not revolve around the Earth. So, what was it that convinced Galileo, fifteen years before he had telescopic evidence, that Copernicus was right? This is especially curious given that the obvious kinematic explanations of the observed motions are compatible with the Brahe model.

However, Galileo's theory of the tides presented in the "Fourth Day" seems to undermine, in at least two ways, his careful work up to that point in *Dialogue.* The first is that it seems to involve retreating to a large extent from his anti-Ptolemaic arguments that are based on the principle that because motion is relative there are no tests that can be performed on the Earth to determine if the Earth is moving. By contrast, and although it is not entirely clear what he means by the phrase, Galileo says that the combination of Earth's motions results in an "absolute motion" of Earth's parts, which is what causes the tides (*Dialogue,* Drake, 1981, p. 496). The second difficulty is that Galileo's tidal theory seems to rely tacitly on action at a distance, which, as was described earlier, Galileo called "repugnant".

In Galileo’s theory the Moon does not act directly on the tides, but it does act indirectly by affecting the motion of the Earth. Galileo attacks the geocentric solar system models of Ptolemy and Brahe, whose model had become the norm by this time, by discrediting the arguments designed to show that the Earth is not moving. He does this by arguing that experiments done on the Earth are unable to prove the mobility of the Earth because they are “indifferently adaptable to an earth in motion or at rest” (*Dialogue,* Drake, trans., 1981, p. 6). For example, consider a common Aristotelian demonstration used for the immobility of the Earth: if a ball is dropped from the top of a tower, it lands at the base of the tower. If the Earth were moving, the ball would fall as far away from the tower as the Earth would have rotated during the ball’s descent, but since the ball does not fall away from the tower, the Earth cannot be moving. Galileo explains why he does not accept this as a proper argument for the Earth’s immobility in the following excerpt from the “Second Day”:

> ...whatever motion comes to be attributed to the earth must necessarily remain imperceptible to us and as if nonexistent, so long as we look only at terrestrial objects; for as inhabitants of the earth, we consequently participate in the same motion. (Drake, trans., 1981, p. 132)

Galileo’s argument is that if the Earth is moving, then the ball is already moving with the same direction and velocity as the top of the tower from which it is released. Hence, contrary to the Aristotelians, Galileo maintains that we should expect to see the ball land at the base of the tower whether or not the Earth is moving. In other words, Galileo’s position is that motion is relative. However, this raises the most compelling question about his tidal theory: if motion is relative, why then does Galileo think the movement of the tides can supply confirmation of the movement of the Earth?[109]

One possibility is that Galileo does not think that motion is relative or at least not absolutely relative. The phrase in the excerpt above that Drake translates as "imperceptible to us and as if nonexistent" could be taken as evidence that Galileo thinks that there is only apparent relativity of motion, but that in fact if our observational techniques were sensitive enough, we could detect effects of the Earth's motion on objects smaller than the ocean. In this case, Galileo would be arguing that rocks dropped from towers and cannon balls shot in opposite directions are in fact affected by the motion of the Earth, but that we are not able to perceive these differences because of their small scale compared with the size of the Earth. Galileo's objection to Ptolemy's tower argument would not be that both the ball and the tower participate in the motion of the Earth, and so do not change with respect to each other. Instead, the focus of Galileo's argument would be that because the ball is so small relative to the Earth, our observations are too inaccurate to conclude, as Aristotle and Ptolemy do, that the Earth is not moving. In this case, Galileo's argument that we perceive small changes in the oceans (the range of tidal motion is miniscule compared with the depth of the oceans) because they are so much larger would be consistent.

[109] In *Dialogue,* "Day Two" there are multiple "experiments" based on the same reasoning: for instance, a cannonball fired perpendicularly to the Earth's surface will have a longer flight time than the ball dropped from the tower, which should give the cannon, which is fixed to the Earth, even more time to move away from where the cannonball will land. There is also a slight variation where two cannons are fired—one eastward and the other westward. The ball traveling westward should greatly outdistance the ball traveling eastward if the Earth were rotating eastward as proposed by Copernicus (Drake, 1981, p. 147).

The fact of Galileo's tidal theory makes the possibility of Galileo's disbelief in relative motion more likely. However, Galileo's "tower proof" later in the "Second Day" argues exclusively from the position that because both the tower and the rock participate in the same motion as the Earth, we expect to observe the same motions whether or not the Earth is moving.[110] Clarifying his argument, Galileo claims:

> It is obvious, then, that motion which is common to many moving things is idle and inconsequential to the relation of these movables among themselves, nothing being changed among them, and that it is operative only in the relation that they have with other bodies lacking that motion, among which their location is changed. (Drake, trans., 1981, p. 135)

I take Galileo's refutations of Aristotle's and Ptolemy's arguments for the immobility of the Earth as compelling evidence that Galileo's argument hinges on the relativity of motion. We are still left then with the difficult task of understanding why Galileo does not think his tidal theory undermines his earlier arguments.

To show that the Earth's movements cause the ebb and flow of the tides, Galileo needs to establish two propositions: (i) that if the Earth were stationary it would be much harder to give any adequate account of the tides; and (ii) if the motion of the Earth does conform to the Copernican model, then these motions will necessarily lead to (something like) the observed tidal phenomena. What needs to be explained is why Galileo thinks the oceans "feel" or react to the motion of the Earth despite his argument that the ball dropped from the tower or projectiles launched from the surface of the Earth are not affected by it.

[110] See Drake (1981: 191-4)

Galileo's theory is that the tides are produced because the sea beds, which *hold* the oceans, shake up the water the same way that water in a basin is sloshed about when the basin is picked up, or one of the water barges carrying freshwater from the mainland to Venice disturbs the water within when accelerated or decelerated (*Dialogue*, Drake, 1981, p. 493). Galileo says that if the Earth had only one uniform motion, i.e. a single motion of constant trajectory and velocity, it could not produce tidal effects alone. However, because there are multiple movements, Galileo argues that the Earth does exhibit its motion through the tides. That the Earth must have two different motions in order to produce tidal effects is the key assertion that Galileo must demonstrate.

The Copernican theory Galileo argues for in the first sections of *Dialogue* involves three regular motions: diurnal, annual, and precessional. None of these constant motions alone, argues Galileo, could produce changes in tidal phenomena and the last is in any case negligible. However, there are changes in tidal phenomena; they change as frequently as the phases of the Moon and Earth's relationship to the Sun. Galileo explicitly acknowledges that the tides are irregular even though the motions causing them must be regular: "that the Mediterranean and all other sea basins (in a word, that all parts of the earth) move with a conspicuously uneven motion, even though nothing but regular and uniform motions may happen to be assigned to the globe itself" (*Dialogue*, Drake, 1981, p. 494). Galileo argues that observable tidal motion is the effect of the combination of the annual and diurnal circular motions of the Earth. These motions combine to produce what Galileo calls "regular absolute motion" of parts of the Earth, but not of the Earth as a whole (*Dialogue*, Drake, 1981, p. 496).

Specifically, at any instant, any two points along the equator on opposite sides of a spinning sphere are moving in opposite directions with respect to the plane of the equator; see Figure 4.4. "A" and "B" are points on opposite sides of a sphere. Points on opposite sides move with different velocities with respect to the inertial frame of reference "P" when the direction of their motions is parallel to the orbital path of the sphere. Thus, from the perspective of an inertial frame of reference, the instantaneous velocity at point "A" is the tangential velocity of that point on the sphere added to the orbital velocity of the sphere. However, from the same frame of reference, the velocity at point "B" is measured by subtracting the tangential velocity from the orbital velocity. Galileo says that the part of the Earth spinning in the same direction the Earth is revolving around the Sun is moving much faster than the opposite part of the Earth, which is spinning in the opposite direction of the Earth's orbital path. Galileo calls this difference one of absolute motion (*Dialogue*, Drake, 1981, p. 496), but does not clearly explain what he means by 'absolute' motion given the context of his earlier refutations of the arguments for the geocentric solar system models.[111]

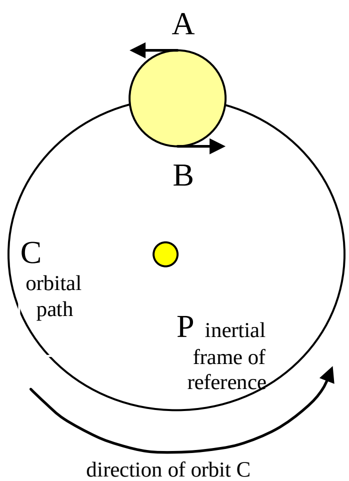

Figure 4.4

[111] It would be nice to know with respect to what Galileo thinks the parts of the Earth are changing velocities; i.e. does Galileo think absolute motion is simply the changing of velocities with respect to the Sun, or the solar system, or does he have some other unidentified inertial frame of reference in mind? The answer to this question is not necessary for the arguments being considered here; however, as a matter of interest to another area in the philosophy of science it might offer insight into another unclear frame of reference that Newton points to in the "bucket experiment" in the General Scholium of *Principia.*

For his tidal theory to meet his own criteria for a scientific demonstration, Galileo needs to justify his assertion that only something the size and viscosity of the oceans could display noticeable effects as a result of the Earth's motions. Justification is needed because the veracity of his claim is not immediately obvious. Galileo does not have an independent way to corroborate his claim about the significance of the magnitude of the oceans. Furthermore, Galileo cannot argue that this claim is entailed by a dynamical theory of mechanics, because Galileo never postulates one. In the absence of other observational data that clearly corroborate this claim, and which are not merely *consistent* with all competing theories, and without a demonstration from a dynamical theory, what remains to justify his claim are on the epistemic level of physical intuitions.[112]

Galileo's justification problem is illustrated by considering the following intuition contradictory to Galileo's intuition that of all the terrestrial bodies, only the oceans reveal Earth's motions. An Aristotelian intuition might propose that if the Earth were moving, smaller bodies would react more detectably than larger bodies. The idea is that a 'force' large enough to accelerate the Earth even a little will be significant enough to throw small things about dramatically.[113] Hence towers, cannons, and people should all *feel,* i.e. be affected by the motions of the Earth Galileo is arguing for. The Aristotelian intuition might propose the following demonstration to support his intuition: place three boats on the ocean: one small punting barge, one medium-sized fishing boat, and one large Spanish galleon. Sail all three vessels in light weather (i.e. small waves) and heavy

[112] See section 4.6 below for discussion of the impact metaphysical influences, such as physical intuitions, have on Galileo's scientific explanation.
[113] The term 'force' is anachronistic; it is only being used here as a place holder for whatever is causing the Earth's motions that Galileo is arguing for.

weather (i.e. large waves). Which vessel most feels the effects of the waves? In light weather the galleon is as steady as the dock while the barge is still noticeably moved. Even in moderate weather the smallest boat is tossed about dramatically while the galleon is gently rocked. From this we can postulate a general rule: (allowing for slight variation due to different hull designs) the larger the boat, the more stable it is. Boats are a good test because they are not fixed to the Earth, which was one of Galileo's stipulations about the ocean. This example is meant to support the contrary intuition to Galileo's, namely that larger bodies should be less likely to feel the effects of the motion of the Earth, as opposed to Galileo's intuition that the oceans feel the Earth's motion in part, precisely because they are so large.

Galileo tries to justify why his arguments for tidal motion are not susceptible to the same counterarguments—i.e. that motion is relative—that he makes to refute the grounding assumption of the Aristotelian arguments for the immobility of the Earth. Galileo postulates that his tidal argument for Earth's mobility is immune to the relative motion counterargument because of two differences between his argument and those of the Aristotelians: 1) relative to the size of the Earth, the oceans are of significant size, and towers and cannons are negligible; 2) the oceans are not *fixed* to the Earth the way towers and cannons are. These are robust observations. Galileo further argues that because different parts of the Earth are undergoing changes in velocity, something fluid and large enough to span significant portions of the Earth would necessarily *feel* the changing accelerations.

The key to Galileo's defense for claiming that only the oceans should exhibit Earth's motion is revealed in his claim that only the oceans 'feel' the motion. The implication is that all terrestrial bodies are affected by the Earth's motions; however, only something as large as the oceans, and as free to move as the oceans, can produce effects discernable to humans. In most coastal areas the tidal rise in water level is only a matter of a few feet; the fact that the tides are so variable is important—it shows that other factors than the motion of the Earth must be operative, since otherwise the motions of the Earth should produce the same effects (at least at similar latitudes) in all bodies of water. Compared to the depth of the ocean, the tides are negligible, but still large enough to be measured by humans. For instance, a percentage change in us that matched the percentage of change in the oceans, would be entirely undetectable to us. This is not the full thrust of Galileo's idea. This is where it becomes essential that Galileo insists that there be at least two distinct terrestrial motions. The two motions accelerate opposite parts of the Earth in contrary directions. Thus, since the oceans span the world, the same body (ocean) is pulled in opposite directions. Now the fluidity is key.

> Among all sublunary things it is only in the element of water (as something which is very vast and is not joined and linked with the terrestrial globe as are all its solid parts, but is rather, because of its fluidity, free and separate and a law unto itself) that we may recognize some trace or indication of the Earth's behavior in regard to motion and rest. (*Dialogue*, Drake, trans., 1981, p. 484)

Because the ocean is fluid, contrary impulses push it just a little, causing the tides. So, for Galileo, it is not a matter of people being accelerated in contrary ways, because we are as a point to the Earth, so we are not pulled in multiple directions. The oceans span the Earth and are not fixed. Some mountain ranges may be large enough to likewise *feel* the contrary accelerations, but because they are fixed to the Earth, we are not able to detect the small contrary accelerations they feel.[114]

This compound effect is not seen in small bodies because they are not subjected to contrary forces. Large bodies, such as the oceans, feel the force, but only very slightly. Galileo remarks that the tidal displacements of a few feet are nothing compared with the depths and breadths of the oceans. The claim is that the parts of a great basin, a big ocean floor for example, are moving unequally in some absolute sense. Galileo must admit that the ends of the ocean floor are not moving relative to one another, but he says that absolutely (or perhaps with respect to an unidentified frame) they are moving very differently: one side is accelerating and moving very fast and the other is impeded, hardly moving at all (*Dialogue*, Drake, 1981, p. 499).[115]

Galileo considers a counterargument to this demonstration in the *Dialogue* by having Simplicio, the character representing the Scholastics, raise an objection based on the lack of a corresponding wind effect. Simplicio suggests that the air should also be sloshed about, causing extremely high, constant winds. Salviati replies, "The air, being a thing that is in itself very tenuous and extremely light, is most easily movable by the slightest force; but it is also most inept at conserving the motion when the mover ceases acting" (*Dialogue*, Drake, trans., 1981, p. 508). Hence, it is because water is heavier than air that we have tides but not as noticeable effects in the air. It is also because this is

[114] In defense of Galileo, someone might have suggested that this force on things like mountain ranges is the cause of earthquakes and volcanoes. And in fact we now believe that there are land tides.
[115] Of course, this is an exaggeration if Galileo has in mind motion relative to the Sun. The maximum tangential velocity of a point on the Earth at the equator is just over 1,000 mph; the orbital velocity is close to 67,000 mph—hence the maximum 'absolute' difference is only about three percent.

supposed to be an acceleration rather than merely a velocity phenomenon, meaning that it is harder to accelerate water than air. However, Galileo uses as evidence the claim that there is a perpetual breeze on the oceans toward the west, between the tropics (*Dialogue,* Drake, 1981, p. 510).[116] European navigators were already well aware of the trade winds by Galileo's time. Galileo is correct that there is some easterliness to the trade winds, which is due to the Coriolis Effect.[117] Simplicio points out, however, that the same wind phenomena would be created if the Earth were stationary and the firmament revolved around it, as in the geocentric models (*Dialogue,* Drake, 1981, p. 512). This is just the kind of argument Galileo uses earlier in *Dialogue* to show how the idea of relative motion invalidates Ptolemaic arguments. The crux of Galileo's arguments against the Ptolemaic system is that Ptolemy's "evidence" does not properly support the hypothesis that the Earth is immobile, because the same effects would be felt with or without the Earth's motion. Thus, by Galileo's arguments that motion is relative, Ptolemaic evidence is inconclusive. The challenge to Galileo's argument, however, is to explain why Galileo's rejection of the Ptolemaic arguments does not also defeat his own tidal theory.

In sum, Galileo's two conclusions about tidal theory are:

(i) "if the terrestrial globe were immovable, the ebb and flow of the oceans could not occur naturally;"

(ii) "when we confer upon the globe the movements just assigned to it [by the Copernican system], the seas are necessarily subjected to an ebb

[116] Predominantly, the trades are caused by the high pressure air that builds up around the tropics moving toward the low pressure system around the equator.
[117] The Coriolis Effect is the apparent veering of bodies toward the right in the Northern hemisphere and toward the left in the Southern hemisphere. This is the effect of moving on a rotating sphere.

> and flow agreeing in all respects with what is to be observed in them." (Drake, trans., 1981, p. 484)

Though Galileo admits there is a strong correlation between the phases of the Moon and the monthly variation in the tidal cycle, he rejects the idea that the Moon has any direct causal impact on the movements of the oceans. Galileo rejects the lunar hypothesis because he does not believe the remote Moon can act on the local water. Galileo admits such a hypothesis calls for "occult" forces (*Dialogue,* Drake, 1981, p. 516). This type of objection is described elsewhere as being "action at a distance." Galileo cannot imagine, or his intuition will not allow, that there might be an invisible force between the Moon and the waters. Galileo's position is not unreasonable.[118] However, Galileo does not go so far as to accept a correlation between the Moon and tides as a coincidence. He comes up with the ingenious hypothesis about the acceleration and retardation of the Earth because of the relative position of the Moon. This makes the phases of the Moon and the tides related phenomena even though they are not linked such that the Moon is directly causing the tides. However, as will be shown below, it is a problem for his hypothesis that Galileo has apparently merely substituted one occult force for another.

Despite his "repugnance" for the thought that the Moon could impact the waters from afar, it is essential to his tidal theory that the Moon impacts the motion of the Earth from afar. Galileo makes the analogy with a weight on a diameter of a clock wheel. As the weight is moved closer to center, the speed of rotation increases (for a constant force). It is not repugnant to the imagination that the weight on a stick should slow down the

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[118] Neither was this an uncommon view; consider the great reluctance of French scholars to accept Newtonian Mechanics well into the 18th century.

gear, because the weight is attached to a stick that is attached to the wheel. There is constant physical contact between them. How does the Moon have this effect on the Earth? Why is this hypothesis not "repugnant" to Galileo?

> Now if it is true that the force which moves the Earth and the moon around the sun always retains the same strength, and if it is true that the same moving body moved by the same force but in unequal circles passes over similar arcs of smaller circles in shorter times, then it must necessarily be said that the moon when at its least distance from the sun (that is, at conjunction) passes through greater arcs of the Earth's orbit than when it is at its greatest distance (that is, at opposition and full moon). And it is necessary also that the Earth should share in this irregularity of the moon. (*Dialogue*, Drake, trans., 1981, pp. 525-526)

Once again Galileo's theorizing raises many questions; for instance, the justification for Galileo's certainty that the force on the Earth and Moon remains constant is unclear. Although it makes for a simpler dynamical theory to suppose that the Earth's speed around the Sun is constant (due to a constant force), this supposition would then require that some other cause also be posited because, in fact, the Earth does appear to change speeds with respect to the Sun. Alternatively, Galileo could take the phenomena of Earth's speed variations as *evidence* that the force moving the Earth around the Sun is not constant. This relates to the earlier discussion about specific weight—how does Galileo decide what theory a given class of observations support? Of course, Galileo wants the simplest explanation (this is also a difficult condition to assess); however, Galileo is a realist, meaning that he believes that his scientific explanations are *true* accounts of the fabric of the world. If Galileo is certain that the force is constant just because it makes for a simpler dynamical theory, then he would be revealing a very strong rationalist component to his method.

4.6 Analysis of Implicit Elements of Galileo's Method

The two case studies above demonstrate methodological factors explicit in Galileo's concept of scientific demonstration. This next section analyzes the complexities necessary to understanding Galileo's method of scientific demonstration. The earlier analysis of Aristotle's method (see chapter 2) will now serve to highlight what makes Galileo's method revolutionary. Because Galileo's biggest critics identified themselves as 'Aristotelian', it is often assumed that Galileo's method is completely contrary to Aristotle's. The Aristotelians of Galileo's time were direct intellectual descendants of the Scholastic tradition, which began when 12^{th} century thinkers first tried to apply Aristotle's treatises on logic to the tradition of empirically based development of technology in the Medieval West. Despite this tradition of trying to understand nature in order to control it, and even more to the point, despite Aristotle's commitment to careful observation, the Aristotelians of Galileo's time had long since abandoned Aristotle's actual scientific methods in favor of some sort of Aristotelian dogmatism. The consequence was that in method, the Aristotelians differed more from both Galileo and Aristotle than Galileo differed from Aristotle. As discussed above, this goes against a long-standing stereotype that says the change from Aristotle to Galileo is the change from Rationalism, based loosely on observation, to strict Empiricism, based on experimentation.[119] The rest of this chapter will show why this stereotype is misleading and what the essential elements of Galileo's method are that need to be considered when developing a better model for scientific explanation.

17th Century Aristotelians

It is easier to explain where Galileo departs from the Aristotelians than to show where he departs from Aristotle, in part, because Galileo takes pains throughout his career to highlight where he thinks the Aristotelians go wrong. In his "Letter to the Grand Duchess Christina" (1615) Galileo says that he believes that his Aristotelian critics have fallen into error because of their overconfidence in trying "to understand by means of reason alone," instead of also relying on extensive empirical observations (Drake, 1957, p. 175). Here, Galileo's professed method diverges from his contemporaries' but is more similar to Aristotle's in trying to make experience and observation the beginning of knowledge and the basis of inquiry.

Galileo goes further in criticizing the Aristotelians. In the "Second Day" of *Dialogue Concerning the Two Chief World Systems* (1632) the character representing the Aristotelian viewpoint, Simplicio, claims of interpreting Aristotle's corpus that, "There is no doubt that whoever has this skill will be able to draw from his books demonstrations of all that can be known; for every single thing is in them" (p. 126). Likewise, in the "Third Letter on Sunspots" (1612) Galileo says of his Aristotelian contemporaries:

[119] For examples of this stereotype see Hall (1962), Koyré (1978). For more discussion about the stereotype in Galileo scholarship, see Cohen (1960).

> So far as I can see, their education consisted in being nourished from infancy on the opinion that philosophizing is and can be nothing but to make a comprehensive survey of the texts of Aristotle, that from divers [sic] passages they may quickly collect and throw together a great number of solutions to any proposed problem. (Drake, 1957, pp. 126-7)

Aristotle's scientific methods seem to have been lost by the Aristotelians by this time and replaced with a sort of literary review approach. Galileo represents them as approaching any new problem as a matter merely for further interpretation of Aristotle's assertions. The Aristotelians assumed that, with the exception of those items of faith corrected by St. Thomas Aquinas, Aristotle had already discovered all of nature's truths.

Discovering what is truly revolutionary about Galileo by comparing and contrasting him with Aristotle is a more complex undertaking. It will be helpful to begin this process by establishing the elements that influence Galileo's thinking that are relevant to this discussion.

Analysis of Influences on Method

To understand what Galileo considers to be a satisfactory scientific explanation, it is necessary to look at the influences on his scientific methods that he does not explicitly discuss. There are three implicit influences on Galileo's philosophy of science, which underlie his method for generating scientific explanations, defined above and illustrated with the case studies. These three influences are: 1) Galileo's metaphysics, which I divide into three categories—worldview (hereafter theoretical framework), metaphysical commitments, and physical intuitions; 2) experiences, i.e. empirical observation, which is often broken into 'experiments' and "mere" observation; and 3) reason, which includes how judgments are made about experiential data and the structure of rational arguments (e.g. Aristotle's syllogisms).

Metaphysics

The first implicit influence on Galileo's philosophy of science is his metaphysics, which I divide into three classifications: theoretical framework, metaphysical commitments, and physical intuitions. Although these three categories are different, they are lumped together under 'metaphysics' because they all have similar impacts on empirical observations and on theory building. They are the same just insofar as they impact the investigation and explanation of science in the same way: (i) they affect the formation of questions one asks about nature; (ii) they affect the rudimentary judgments about what one has observed; and (iii) they affect the range of possible explanations that satisfactorily answer those questions. These three differ along a continuum that ranges from less conscious/deliberate with a greater impact on one's scientific investigations, to the more conscious/deliberate with lesser impact on one's scientific investigations. Theoretical framework, metaphysical commitments, and physical intuitions cannot be sharply differentiated; instead the continuum on which they lie has fuzzy boundaries. This is so because the status of a particular metaphysical influence can be different for different people and can change over time for the same person. For instance, something may start as an intuition and then become a conscious metaphysical commitment. Or an intuition could become a part of one's theoretical framework directly without ever being a conscious metaphysical commitment. Ockham's Razor, for example, is taken by some to be an intuitively justifiable rule of thumb for theory building while for others the razor is a deliberate metaphysical commitment to the orderliness of nature and the connection between human understanding and the intelligence responsible for nature's orderliness. For others, the razor is merely an intuitively useful rule of thumb in the process of creating new theories and is consistent with scientific instrumentalism. It is also possible that a version of the razor could be an implicit part of someone's worldview before she becomes conscious of the influence it may have on theorizing and then deliberately removes it. Although there are not clear lines that differentiate these three metaphysical influences on conducting science, we can give examples where it is generally more appropriate to use one term over the others.

One's theoretical framework has a strong impact on what questions need to be asked and answered because it determines what phenomena need explaining. For example, are we trying to explain why the Moon, being perfect and ethereal, has spots? Or do we need to explain why the Moon, which has shadows because it is a large rock like the Earth, stays in the heavens instead of falling on us? Do we need to explain why projectiles keep moving after they have left the thrower's hand, or do we need to explain why objects stop moving once they are imparted with motion? Metaphysical commitments have a similar impact on what questions need to be asked, but can be a little more deliberate/conscious. Additionally, frameworks are revisable in a way in which metaphysical commitments (at least in theory) are not, because frameworks can be influenced by observations more directly (and unconsciously) than metaphysical commitments can be. For instance, are we beginning from the assumption that the heavens must be perfect and so they must travel in the most perfect shape, circles? Or is the movement of the heavens an open question? In this case it makes sense that the Ancients arrived at circular motion. Because the heavens appear to move regularly, there seemed to the Ancients to be only two possibilities for the paths of heavenly bodies: either the paths are straight or they are curved. However, the paths could not be straight because the universe was considered to be finite, so the regular curve that ancient geometers were left with was circular. The latter allows for Kepler to figure out a simpler model based on curved but not circular motion (i.e. elliptical motion). 'Physical intuition' is similar to theoretical framework and metaphysical commitment, but intuitions tend to be the most plastic. In one sense intuitions might be called *unconscious* metaphysical commitments because we do not always consider where particular intuitions come from, but they are nonetheless more deliberately applied because they suggest possibilities for us to consider.

Despite these differences in metaphysical *degree*, theoretical framework, metaphysical commitment, and physical intuition have a similar constraining impact on theorizing when they narrow the field of what one considers to be possible explanations. Toulmin (1961) stresses the idea that science is not merely the recording of new observations but instead is our interpretation of new observations within the context of our previous theories and metaphysics:

> ...in studying the development of scientific ideas, we must always look out for the ideals and paradigms men rely on to make Nature intelligible. Science progresses, not by recognizing the truth of new observations alone, but by making sense of them. To this task of interpretation we bring principles of regularity, conceptions of natural order, paradigms, ideals, or what-you-will: intellectual patterns which define the range of

> things we can accept (in Copernicus' phrase) as 'sufficiently absolute and pleasing to the mind'. An explanation, to be acceptable, must demonstrate that the happenings under investigation are special cases or complex combinations of our fundamental intelligible types. (p. 81)

In this excerpt, Toulmin makes it clear that our scientific understanding is not objective. The fact that our scientific explanations rely on and are constrained by our metaphysics is useful when it facilitates finding an explanation that meets one's criteria, perhaps by narrowing the field of possible explanations; and of course, this constraining effect is detrimental when it hinders finding a satisfactory explanation because it has eliminated the "correct" explanation. An example of this is seen when Galileo eliminates the possibility that the Moon directly causes tidal phenomena. This problem of potentially eliminating the best explanation is unavoidable in the sense that every stage of scientific investigation relies on one's metaphysics. So, the goal of clarifying these elements is to aid in figuring out the best way to be deliberate about what metaphysical underpinnings are influencing our work and how to avoid errors due to them and how to revise our metaphysics based on new information.

Determining the metaphysical basis for Galileo's commitment to something like Ockham's razor highlights the significance of his metaphysics. The language of the scientific instrumentalism versus scientific realism debate can also be helpful for looking at the metaphysical underpinnings of one's theories. An instrumentalist viewpoint might take Ockham's razor merely as a general guideline for building theories—i.e., as a desirable condition for theories, but one that is trumped by other factors such as ease of use or greater generality or applicability. A realist committed to the razor, on the other hand, might take the razor as representing her metaphysical view that the universe is actually the simplest possible; and hence, simpler theories are more likely to be true theories. Of course both instrumentalists and realists are committed to devising models that fit with conditions such as empirical fit. Galileo turns out to be committed to the metaphysics of orderliness. This goes hand in hand with his scientific realism. Although, realism is not an all or nothing proposition, that is, one can be realist about some things but not others, there could have been no dispute between the Copernican and the Brahe views, no fight between Galileo and the Church, except on the basis of realist commitments. The nature of his realism will be made clear later by considering his commitment to the mathematical structure of nature.[120]

Experience

The next element to consider is how experience shapes Galileo's theories in the empirical sciences. Going at least as far back as Kant (1781), the difference between Aristotle's method of empirical observation and Galileo's has been characterized as the

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[120] One piece of evidence supporting the claim that Galileo is a realist comes from his strong desire for the terms of his appointment to the Tuscan court in 1610 to recognize him as a philosopher and not just as a mathematician (Drake 1957, p. 64). Drake claims that it was Galileo's work in astronomy and mathematics in *The Starry Messenger* that made Galileo an overnight celebrity and inspired his former pupil, Cosimo the Grand Duke of Tuscany, to make Galileo his chief mathematician. So why, then, was Galileo also concerned with being called a philosopher? What did it mean to be a philosopher at this time? For Aristotle, the paradigm of philosophy is first philosophy or metaphysics, which is an investigation into substances and their causes, especially the final cause; this investigation requires investigation into and acquaintance with first principles. Although Galileo rejects science being the search for 'final' causes, as seen in the excerpts from *Floating Bodies,* Galileo is still interested in proximate causes just insofar as they provide explanatory power to demonstrations. So, this line of reasoning suggests that Galileo wanted to do more than just accurately record celestial positions; he might want the title "philosopher" in order to emphasize his interest in answering "why" questions behind the appearances. If it is going too far to take Galileo's desire for the title 'philosopher' as evidence of his interest in causation, one could still infer from this desire that Galileo wanted the credentials and institutional backing to enter into debates with the Church astronomers not just about the workability of the models but actually about cosmic architecture.

difference between “mere” observation and ‘experimentation’. In this sense, experiments involve asking specific questions about natural phenomena and then designing experiments in such a way that the ‘variable’ being tested can be isolated. The difference is that in experiments, what is observed is the result of a specific, predetermined plan; whereas, according to this characterization, observations made outside of experiments are supposed to be a matter of chance. Experiments try to *artificially* simulate phenomena or to generate them in conditions in which ‘noise’ has been filtered out. One example of this in Galileo’s corpus is his inclined plane experiments. He used an inclined plane to determine the law that explains how bodies accelerate during free fall. The three possible factors were length of time of acceleration, distance traveled during acceleration, and the vertical height traveled during acceleration. In this case the incline allowed Galileo to experimentally measure acceleration by translating the final speed reached by a ball released along an inclined plane into the distance the ball traveled after being launched horizontally. Galileo kept the vertical height of release constant while varying the angle of the incline, and hence the length of time the ball spent accelerating along the track. He found that the distance the ball landed from the track was constant when the vertical height remained constant, independent of the angle of incline. From this Galileo was able to isolate the variable that determines the speed reached through acceleration, namely vertical height traveled and not distance traveled during acceleration or length of time of acceleration.

The advantage to ‘experimenting’ as opposed to “merely” observing is that experiments tend to make more clear what question is being asked, or what is being tested. This idea is expressed by Kant in his explanation of the differences between modern and ancient science. In the quotation that follows, Kant is characterizing what is new about the methods used by moderns such as Galileo.

> They learned that reason has insight only into that which it produces after a plan of its own, and that it must not allow itself to be kept, as it were, in nature's leading-strings, but must itself show the way with principles of judgment based upon fixed laws, constraining nature to give answer to questions of reason's own determining. Accidental observations, made in obedience to no previously thought-out plan, can never be made to yield a necessary law, which alone reason is concerned to discover. Reason, holding in one hand its principles, according to which alone concordant appearances can be admitted as equivalent to laws, and in the other hand the experiment which it has devised in conformity with these principles, must approach nature in order to be taught by it. It must not, however, do so in the character of a pupil who listens to everything that the teacher chooses to say, but of an appointed judge who compels the witnesses to answer questions which he has himself formulated. (*1st Critique,* Kemp-Smith, trans., 1929, p. 20)

Kant's purpose in explaining this change to experimentation made by the moderns is to make the analogy to his theory that all experience presupposes organization into some sort of causal framework. Kant's theory strongly supports the idea that all observations are post-theoretical. The point of the passage above is to explain that the innovation of the moderns in collecting empirical data was to construct specific frameworks—the experimental set-ups—that would answer the specific questions they wanted answered. Kant is contrasting this method with Aristotle's "accidental" observations. Kant is rejecting Aristotle's idea that the way to learn about nature is to be actively passive; i.e. to work at being open enough to receive the forms nature confronts us with.

However, Kant's criticism of Aristotle's epistemology in the excerpt above is overstated. Aristotle's intuition that by removing objects from their natural settings we are only learning about how they behave in these artificial settings is not unreasonable. The stereotype about the change from the Aristotelian system to the modern conception of nature involves the story that it took Galileo, Bacon, and Descartes to begin experimenting in the Baconian sense of putting nature "on the rack". The assumption is that any controlled experiment would be viewed by Aristotle as having taken nature out of context. The Kantian criticism that observations are somehow random and can never be guaranteed to give a full picture of a system should be separated from the idea that Aristotle thought it important to get his "hands dirty." Galileo for instance, was aware of the importance of experience to Aristotle's method. In the "First Day" of *Dialogue,* Simplicio says:

> Aristotle would not give assurance from his reasoning more than was proper, despite his great genius. He held in his philosophizing that sensible experiments were to be preferred above any argument built by human ingenuity, and he said that those who would contradict the evidence of any sense deserved to be punished by the loss of that sense. (Drake, trans., 1981, p. 36)

This illustrates some of the similarity between Aristotle's and Galileo's methods, especially the importance of sensate experiences to both, while revealing how the 17th century Aristotelians are farther removed from both Galileo and Aristotle than they are from each other. However, there may be a meaningful difference between Galileo and Aristotle with regard to thought experiments and experiments designed to eliminate "natural" influences such as air resistance.

Although Aristotle allows for some thought experiments involving counterfactuals (e.g. the proof of the impossibility of void, *Physics* IV.8), he would likely disagree with Galileo about the value of what is learned by constructing *unnatural* conditions with which to test natural phenomena. For example Galileo wants to know how objects would fall in a vacuum, i.e. how they would fall in an *ideal* space. Aristotle would argue that it is not helpful to think about how objects would fall where it is (in his view) *in principle* impossible for them to fall. Furthermore, Aristotle would not think one could learn anything about how things happen in nature by devising thought experiments or physical experiments designed to remove objects from nature. Galileo, on the other hand, thinks that experiments designed to simulate the *ideal* are better able to reveal nature's truths.

It would be false to say that Aristotle is not interested in *ideal* solutions; after all, the universals that Aristotle reasons to from observations of particulars are all *ideal* in this sense. However, they are not *idealized*, i.e. mathematical fictions abstracted from imperfect data the way Galileo does. Aristotle tries to account for the deviation in nature from the ideal by introducing the caveat that many things in nature happen "always or for the most part". In fact, in Aristotle's science it is possible for an occurrence to be relatively infrequent and still be the *natural* effect. For example, Aristotle argues that by nature, acorns become oak trees. This is true even though he acknowledges that only a small percentage of acorns become trees, the vast majority are squirrel food, and only a small percentage of fish eggs become fish. So, both Aristotle and Galileo are able to think in terms of explanations involving ideals while allowing for deviation. One difference between them is that Galileo strives to find a formula that can predict phenomena, while Aristotle wants to find the complete account of how particular phenomena fit within the whole of nature. Another difference between Aristotle and Galileo is that despite recognizing that nature does not always exhibit what is most *natural*, Aristotle still does not try to manipulate nature in order to reveal the ideal. Galileo's idealizations aim at the mathematically regular. For example, he wants a simple formula for free fall or the periods of pendulums that predicts behavior when certain factors are accounted for, such as air resistance, even though these complicating factors are more prevalent than squirrels eating acorns.

Reason

In addition to the differences between Galileo and Aristotle in terms of the elements of metaphysics and experience in Galileo's scientific work, there are also important differences between them in terms of the role that reason and rational arguments play in their theories. Reason plays two fundamental roles in the formation of Galileo's scientific explanations. First, by interpreting an experience, reason judges what one saw. In this role reason is the mediator between the raw sensory input and one's metaphysics, which constrain to a certain degree what is possible for one to *see*. Reason's second role is in determining what a set of observations is in support of, i.e. what is the best explanation or model that accounts for the phenomena. In both cases reason is judgment.

Empirical theory creation is facilitated by applying reason to empirical observational data. For example, interpreting rudimentary observations can be like making a coherent story from a disordered series of pictures: the general understanding the interpreter already has that she brings to any new set of pictures influences the story that can be made from them. A different general understanding or theoretical framework will yield a different story from the same experiences. This is illustrated by the account of the famous free fall experiment at the Leaning Tower in Pisa.[121]

Galileo intended to disprove the Aristotelian notion that heavier objects fall faster than lighter objects, over the same distance, in the ratio of their weights (*Physics* IV.8). From the top of the tower a cannonball and a musket ball were released from the same height as close to simultaneously as could be done at the time. Galileo and his Scholastic critics observed the same event and recorded the same data: both sides agreed that the heavier object, the cannon ball, landed before the much lighter musket ball. However, both sides felt equally vindicated in their opposing interpretations and conclusions. For which of the two competing theories is this event evidence? The Aristotelians felt vindicated because the heavier object moved faster, as Aristotle predicted (although not dozens or hundreds of times faster as it should, based on the ratio of their weights). Galileo, on the other hand, believed that the heavier object only landed before the lighter object because the lighter object's motion was more greatly impeded by air resistance.

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[121] Whether Galileo actually conducted this experiment himself or not remains controversial. However, it does seem clear from the historical record that a version of this experiment was conducted in Pisa and that either Galileo participated in it or it preceded him. In either case, Galileo was aware of the results (Drake, 1980). There is evidence from his notebooks that Galileo did conduct his own free fall experiments like those conducted at Pisa (Lindberg, 1992).

Again, both camps agreed about the rudimentary observation, but they made different judgments about the single event.

The two camps made different judgments because each side had brought a different theoretical framework to the experiment: the Aristotelians' framework required that heavy objects fall faster than light objects because they contain more earth in them, which is what causes them to move downwards; Galileo's framework, on the other hand, required that all objects fall alike, except when resisted. So, just as people with very different perspectives will make different stories from the same pictures, there is a sense in which Galileo and the Scholastics *saw* something different from each other. Hanson (1958) argues that, "seeing is a 'theory-laden' undertaking. Observation of *x* is shaped by prior knowledge of *x*" (p. 19).[122]

Because an observation is an interpretation or judgment, and because interpretation necessarily requires at least a rudimentary theoretical framework, a theoretical framework is another necessary condition for the possibility of making an observational judgment.[123] There is a difficulty, however, because observational judgments both come from and inform theories. The challenge is to explain how Galileo was able to reason from the *same* event the Aristotelians witnessed to a much richer explanation of falling bodies. One important aspect of this issue concerns the extent to

[122] For further discussion see Kuhn (1996) chapter 10, for a discussion about the impact of theoretical frameworks on observations. Among others, Kuhn gives the example of how the Aristotelians saw the pendulum as a body repeatedly "falling with difficulty" slowly coming to rest, overcoming the effect of being suspended by a cord; whereas Galileo saw the pendulum as almost continuously repeating its motion, except for what is lost through resistance (p. 119).

[123] The challenge to philosophers of science is to clarify this dialectical interaction that must take place. In addition to Kuhn (1996), for the status of the contemporary debate about the theory laden-ness of observations, i.e. whether pre-theoretic observations are possible and if so how there can be a genuine distinction between observational and theoretical terms and sentences in sciences, see: Psillos 2002; Hempel 1965; Hanson 1958; Popper 1934a, 1934b, 1960..

which one is prepared to allow experience to correct a theory—in other words, how falsifiable the theory is, and what one is prepared to admit as disconfirming evidence.

One example of Galileo's willingness to trust his theory over physical evidence is his experimental attempt to determine the speed of light. Galileo sent an assistant with a lamp to the top of one hill while Galileo, also equipped with a lamp, went to the top of another hill. The idea was to be as far apart as possible while still being within sight of each other. The lamps had shutters that blocked the light from being visible to the opposite observer. Knowing the distance between the two hilltops, Galileo knew he could calculate the speed of light if he could measure the time it took for light to travel from one hilltop to the other and back. Galileo's plan was to measure the elapsed time between Galileo's opening the shutter on his lamp, the assistant seeing the light from Galileo's lamp and then immediately opening the shutter on his lamp and then Galileo's seeing the light from the student's lamp. Galileo was surprised to find that he could see the light on the other hill coming back to him before he had even fully opened his lamp. Allowing for reaction time, the light seemed to be traveling instantaneously. Remarkably, Galileo did not conclude that the speed of light is infinite. He concluded instead that to measure the speed of light the lamps needed to be farther apart than was feasible to allow observation. This is an example of very careful reasoning. It would have been reasonable to conclude, as others did, that light travels instantaneously. However, Galileo does not take pains to ensure that his reasoning from observation to theory is always this careful by being explicit about what would confirm or disconfirm the theory that light travels instantaneously.

Further insight into Galileo's conception of the complicated dialectic between experience and theory can be gained by considering more closely the significance of his use of idealization in theory building. Experience does not provide examples of the ideal; e.g. pendulums come to rest, falling objects do not reach the ground simultaneously, and balls released from the same height on an inclined plane leave a *range* of marks on the floor instead of a single mark. The free fall experiment exemplifies this quandary. Galileo felt justified in his confidence that the disturbing factor was air resistance and that the air resistance was enough to account for the discrepancy between ideal and actual conditions.[124]

The problem of mediating the dialectical interaction between experience and theory can be understood in two ways: First, reason is the tool that judges whether experimental variation from the hypothesis is due to the experimental technique or some factor unaccounted for in the hypothesis being tested. In the case of free fall, even if an air resistance factor is posited that makes the observational data fit the hypothesis it will be susceptible to the criticism that positing this air resistance factor is *ad hoc*. The only way to defend against the charge of making *ad hoc* additions to a theory is to design further experiments that will independently corroborate that air resistance accounts for variation from expected results. These experiments will likewise produce *imperfect* results, which again will need to be judged in order to ascertain whether the new results are due to imperfect experimental technique or some other still unaccounted for factor.

[124] Aristotle, as well as the Scholastics, held that the rate of fall is an inverse function of the resistance of the media; however, there does not seem to have been any attempt to work out how media might resist differently depending on the mass and volume of a body, or any attempt to measure resistance. In fact, they were not interested generally in measurement as such.

Observational data alone cannot by themselves determine a theory; it is always necessary to interpret the data in order to form a theory, which requires reason.

This invokes the second aspect of this problem, which can be seen as a part of the general problem of (enumerative) induction in the empirical sciences.[125] Even a close fitting factor that accounts for air resistance in the experiments possible at Galileo's time cannot, in principle, be proved accurate for all possible experiments. Galileo does not explain how he can be sure that his experimental observations are capturing how objects will fall in the future any more than Aristotle explains how he can be sure that his generalizations accurately represent a class of phenomena. When Kant is praising Galileo's method over Aristotle's he does not acknowledge this similarity between Galileo and Aristotle. The suggestion being put forward here is not that empirical science is untenable because it necessarily relies on induction; the point is that any fully developed theory of scientific explanation ought to explicitly address the problem of induction as it applies to positing things like natural laws.[126] By induction, and like induction itself, its continued usefulness seems to be good grounds for continuing its use.[127]

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[125] One way to characterize the problem of classical induction (now called enumerative induction) is that there is not a theoretical way to distinguish between good and bad inductions; any attempt to justify an induction in empirical science would rely on induction, and hence be circular. See: Hume's *An Inquiry Concerning Human Understanding,* Section IV; Goodman (1983), "New Riddle of Induction" in *Fact, Fiction, and Forecast.*

[126] Lange (2000) argues that inductive confirmation is only appropriate for things like natural laws because induction relies on the "principle of the uniformity of nature". Lange argues that "we cannot confirm *h* inductively if we believe that $\neg\Box h$ [it is not necessary that *h* is the case]" (p. 121). Hence, we must assume that there are natural laws and that they are necessary, in order to achieve inductive confirmations in the empirical sciences.

[127] Furthermore, there is no alternative substitute for induction in generating theories in the empirical sciences. (Notwithstanding Popper's (1934) attempt at making the structure of scientific progress deductive through his theory of Falsificationism.) Aristotle did not see induction as problematic because he believed

The question of how Galileo adjudicates between reason and empirical data is related to the earlier question of what first persuaded Galileo of the truth of Copernicus' hypothesis. What convinced him that there was something true about Copernicus' theory even though it seems to violate our common sense judgment that we are not spinning around extremely fast? It is not a case of a new theory immediately giving more accurate predictions than the old. Galileo must have been initially persuaded by rational argument rather than empirical data. A closer look at the free fall experiment will serve to fill out Galileo's understanding of the role of rational argument.

There are three relevant topics broached by the free fall experiment: (i) as discussed above, this experiment reveals the critical impact that an observer's theoretical framework has on the interpretation of experiences. Galileo is similar to the Aristotelians insofar as both camps tolerated deviation in the actual results from the theoretically expected results. Galileo was confident that the observed results were within the limit of the expected results adjusted for air resistance. The Aristotelians accepted results that differed from the abstract, mathematical predictions of Aristotle because they were not concerned with mathematics in general, and especially not quantitative measurement (recall that Aristotle predicts that two bodies will fall in the ratio of their weights). It is the attitude toward mathematics that reveals the change from the Aristotelians to Galileo:

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that, for the most part, humans just tend to be able to correctly identify the correct universals based on observations. Being more epistemically incredulous, we suggest that relative levels of inductive justification need to be built into models in the empirical sciences.

for Galileo, our understanding of nature is essentially mathematical, i.e. what it means to understand some phenomena is to have a mathematical model of the phenomena.[128]

Galileo's emphasis on mathematics leads to (ii), the second point to be considered about the free fall experiment: the relative lack of importance of mathematics to Aristotelian science is highlighted by the fact that the Aristotelians were not deterred by the very large deviation from the predicted mathematical results, and instead were satisfied that the general relation held of the heavier hitting before the lighter. And (iii), the third point is that Galileo satisfaction with, and even expectation of some deviation from the ideal case, in which the two balls reach the ground simultaneously, reveals that what is more important is discovering the mathematically regular explanations, which he believes underlie the imperfect events in the physical world. An in depth look at point (i) will serve as a context for discussing (ii) and (iii) later.

Point (i) above is important to the overall question of Galileo's views on reason versus experience because it shows the sense in which the theoretical is prior to experience. This may be more clearly seen in the arguments the Aristotelians made against the use of the telescope for gathering celestial data. The Aristotelian idea was that celestial bodies are composed of different material from terrestrial bodies and further that celestial bodies move in a different medium. For the Aristotelians, this means that the heavens should have a science unique to them; any similarities, or the ability to use similar equipment, such as the telescope to investigate two different realms, would have

[128] This is very different from what Aristotle considers necessary for 'understanding' phenomena, i.e. having scientific knowledge. Without a causal explanation (preferably giving the final or formal cause) one does not have scientific knowledge according to Aristotle. See chapter 2.

to be explained or argued for independently. An explanation common during Galileo's time for the Moon's uneven coloring claims that different parts of the Moon absorb and emit light differently (Van Helden, 1989, p. 11). Galileo was not so influenced by a commitment to a perfectly spherical Moon that he was constrained to explain away the obvious interpretation of the visual data collected meticulously night after night. The Aristotelians rejected Galileo's explanation that the different coloring on the Moon came from mountains and valleys on the Moon as "repugnant" to sense. Galileo was also able to *see* an uneven Moon because his prior-to-the-fact reasoning held that one should begin with the idea that the same observational data should be attributed to the same causes if the same conditions hold.[129] In this case the reasoning is the inference from the understanding that dark spots on the Earth are shadows caused by uneven surfaces, to the same cause of dark spots on the Moon. This conceptual framework had to be in place before Galileo could discover a bumpy Moon.

The example further demonstrates that experience alone cannot dictate explanations; experience is more helpful after the reasoning has been employed. If this were not the case, it would be possible to be convinced by arguments such as those against the motion of the Earth and in favor of the Aristotelian concept of free fall. A rapidly spinning Earth seems to violate common experience. However, starting from the position of disallowing theories that violated common sense had stalled scientific progress. This leaves open the question of how to know when we have the right explanation.

[129] Of course, the Aristotelians would assent to the same principle, but they nevertheless disagreed with the starting assumption that the same conditions might hold for celestial and terrestrial bodies.

Galileo's method of demonstration reveals his concern for certain epistemological problems, which Aristotle seems to be less concerned with, and reveals his lack of concern for other epistemological problems. Galileo's rejection of pursuing the answer to questions such as why things fall, why the celestial bodies revolve, and why certain objects are denser than others, evinces Galileo's caution against theorizing about matters which cannot be empirically justified. However, Galileo's confidence that he is able to determine all of the plausible explanations for a given phenomenon reveals a lack of concern for anticipating error, which is a fundamental epistemological problem.

Mathematical Nature

Although many of the descriptions to this point sound as if Galileo is interested in mathematics and Aristotle is not, this is not strictly accurate. Both Aristotle and Galileo use mathematical proofs in demonstrations about physical phenomena. For example, Aristotle claims that the ratio 2:1 is the formal cause of the octave; Galileo claims that the distance objects fall varies proportionally to the squares of the times they have been falling. If there is a difference on this level, it is that the mathematical formula is the aim, it is the end of the scientific investigation for Galileo, while it may only be a part of the picture for Aristotle. The major difference, however, lies in Galileo's expanded use of mathematics in the investigation of nature. He is interested in quantifying phenomena. This is not something that either the Aristotelians or Aristotle were concerned with. The main point is that while Aristotle gestures towards mathematics, mostly as an exemplar of justified certainty in the sciences, Galileo actually *uses* it. Of course this is oversimplified – there is the model of the Aristotelian mixed sciences, but that is mostly just a model; and even where it is filled out, the use of geometry and arithmetic is largely piecemeal. For example, although in *Physics* IV.8 Aristotle claims that the speed of fall varies as a positive function of the weight of the falling body, there does not appear to be any evidence that the mathematical component of his theory of falling bodies held any import to him. It is very unlikely that Aristotle tried to acquire observational evidence to support his mathematical assertion.

This second change, the quantification of nature, marks a significant divergence from Aristotle's thinking. Once Aristotle has explained the reason for a phenomenon such as free fall, for instance, he is not generally interested in the practical task of measuring it. This is because measuring the particular speeds, even if Aristotle had reasonable means of doing so, would not tell him more about why things fall. Moreover, in *Metaphysics* VIII.3 Aristotle implies that measuring introduces error, and so the more accurate sciences are the ones that do not involve measurement: "We find greater exactness where there is no magnitude, and the greatest exactness where there is no motion" (Tredennick, trans., 1935, 1078a9). This highlights one of Galileo's great innovations in the philosophy of science. Whereas Aristotle does not have an independent way of choosing from among competing explanations, Galileo's preference for quantified predictive accuracy is an empirically justifiable method for evaluating explanations and theories.

Point (ii) above, about how mathematics is not central to Aristotelian science, further highlights the difference between experience in the Aristotelian system and experience in the Galilean system. The lack of concern about the failure of Aristotle's mathematical predictions shows the mathematics or at least mathematical precision to be a secondary consideration for the Aristotelians: they do not expect the theory to yield precise, verifiable predictions. The main point for them is that heavier objects fall faster in this world, and they do not care about abstract worlds. Galileo's conviction that this is the Aristotelians' conception of mathematics is evident in "The Second Day" of *Dialogue* where the conversation is about the value of applying mathematics to the material world. Sagredo claims that trying to deal with physical problems without geometry is impossible and Simplicio (representing the Aristotelian view) responds that there is no significant value in applying math to nature because mathematics does not capture the way bodies actually are: "After all [gentlemen] these mathematical subtleties do very well in the abstract, but they do not work out when applied to sensible and physical matters" (Drake, trans., 1981, p. 236). This attitude, however, runs contrary to a central aim of Galileo's, which is to find useful theories through building mathematical models of natural phenomena. McTighe (1967) captures the challenge to Galileo: "The Aristotelian claim that the science of mathematics and the science of nature move on two quite different planes of abstraction, and that natural science must therefore seek an appropriately *physical* explanation of nature, had to be met head on" (pp. 365-366).

There is an apparent paradox in modern science inherited from Galileo. Galileo, who was interested in making the focus of science the application of theory to the empirical world, made greater progress by thinking about what is not the case, i.e. idealizations and the mathematically abstracted, than the Aristotelians were able to make, because they did not allow “false” models. Levins (1966) gets to the heart of the epistemological question about the use of models to represent nature:

> For all models are both true and false. Almost any plausible proposed relation among aspects of nature is likely to be true in the sense that it occurs (although rarely and slightly). Yet all models leave out a lot and are in that sense false, incomplete, inadequate. (p. 430)[130]

The value of a model is measured by how accurately it represents the phenomena being studied and how well it lends itself to further, testable hypotheses. Galileo’s work on floating bodies, his attempt at using the Medician stars to solve the longitude problem, his models of free fall and the motion of the pendulum, and his work on the military compass, among other examples, strongly imply that he is looking for mathematical principles that can be used to predict phenomena, not just to explain past events. Galileo’s commitment to mathematically demonstrable regularity is the point of (iii) above.

As we see in the *Assayer* Galileo has a different metaphysics from Aristotle.

> Philosophy is written in this grand book, the universe, which stands continually open to our gaze. But the book cannot be understood unless one first learns to comprehend the language and read the letters in which it is composed. It is written in the language of mathematics, and its characters are triangles, circles, and other geometric figures without which it is humanly impossible to understand a single word of it; without these, one wanders about in a dark labyrinth. (Drake, 1957, trans., pp. 237-238)

[130] Cartwright (1983) says that there are two aims of scientific theories: one is to tell us what is true in nature, the other is tell us how we can explain it; she argues that these two things are entirely different and should be kept distinct (p. 44).

It may be this “dark labyrinth” that Kant has in mind in his criticism of Aristotle’s epistemology. The generality of mathematics is important to the Modern and contemporary scientific projects because quantification facilitates being able to judge how well experiments are reproduced because of better measurement, and more easily facilitates the use and the sharing of scientific knowledge through a common language. Galileo’s colorful ode to mathematics suggests the comparison between geometrical propositions being deduced from axioms, and knowledge about the world coming from Galileo’s mathematically regular principles. This raises the question of whether Galileo is a mathematical Platonist.[131]

In a certain sense Galileo’s Platonism appears to be clear from his belief that the world is written in the language of mathematics. He is closed off to the possibility of random and irregular physical happenings in the following way:

> There is no doubt whatever that by introducing irregular lines one may save not only the appearance in question but any other. … Lines are called regular when, having a fixed and definite description, they are susceptible of definition and of having their properties demonstrated. … Irregular lines are those which have no determinacy whatever, but are indefinite and casual and hence indefinable; no property of such lines can be demonstrated, and in a word nothing can be known about them. Hence to say, ‘Such events take place thanks to an irregular path’ is the same as to say, ‘I do not know why they occur.’ The introduction of such lines is in no way superior to the ‘sympathy,’ ‘antipathy,’ ‘occult properties,’ influences,’ and other terms employed by some philosophers as a cloak for the correct reply, which would be: ‘I do not know.’ That reply is as much

[131] One of the difficulties in answering this question derives from the inconsistency in the literature about what the term “Platonist” should refer to. A strong form of Platonism would imply a commitment to Platonic metaphysics. Adjusting what Platonism means to the scope of the question being asked here, it will be sufficient to determine what Galileo thinks is the ontological status of mathematical objects and whether he believes the structure of nature is inherently mathematical.

> more tolerable than the others as candid honesty is more beautiful than deceitful duplicity. (*Assayer*, Drake, trans., 1957, pp. 240-1)

Galileo's Platonism appears implicit in the idea that to understand any phenomena one needs to use regular lines, shapes, and other geometric or mathematical properties about which precise demonstrations are possible. However reasonable the leap to Platonism seems, it is not as defensible as the position that Galileo is only making an epistemological claim and not a metaphysical claim about the universe. Though it may be true that it would be more difficult to make causal claims about phenomena if they were irregular, there remains the question of whether or not there can be or are irregular things in nature. Galileo's claim in the quotation above is that what it means for us to know something about natural phenomena is that we can describe it in regular terms. Mathematics is ideal for this purpose, so mathematics is an excellent tool for our knowing things about nature. This is not the same as assuming that the structure of nature is inherently mathematical.

There are two possibilities for Galileo's position on the mathematical nature of the world. The first possibility, and the importantly weaker claim, is that the only things we can meaningfully explain are regular, and so only the phenomena that admit of being described with mathematical regularity are objects for the study of empirical science. The second possibility is that irregularity is only in the appearances and that underlying it are mathematically understandable phenomena—the universe just is mathematical. We can put this question directly into terms relevant to the investigation here about Galileo's concept of scientific demonstration. What exactly is a demonstration in the empirical sciences: is it that, given the assumption of a certain mathematical function's obtaining in nature, certain predictable results can be seen to follow? Or is it the claim that the facts of predictive success establish the truth (or at least highly confirmed plausibility) of the postulated function? Because Galileo never directly discusses his metaphysical views about this, it is not possible to know for certain.

I argue that Galileo believes that the basic structure of nature is mathematical, and this is why he claims that his explanations can be known with complete certainty. The idea is that to the extent that nature is mathematical in character, mathematical demonstrations about natural phenomena should hold with the same degree of certainty as purely mathematical demonstrations do. My argument that Galileo believes that the basic structure of nature is mathematical is based on three pieces of evidence: (i) Galileo's apparent realism; (ii) Galileo's acceptance of Copernicanism contrary to common experience and many years before Galileo had physical evidence that there were other centers of motion in the solar system; and (iii) Galileo's claims that we can know the truth of an explanation with complete certainty, which is illustrated by his comments in the two case studies. More importantly, the second part of what I am claiming is that, although Galileo's views do impact his ability to implement his own three-part method of generating scientific explanations, his metaphysical beliefs about the mathematical nature of the world do not affect our ability to evaluate his method.

The following quotation speaks to Galileo's desire for rigor, even though we have seen that it is not always achieved.

> Salviati: …from our Academician who made many speculations about this subject, all geometrically demonstrated, according to his custom, in such a way that not without reason this could be called a new science. For though some of the conclusions have been noted by others, and first of all by Aristotle, those are not the prettiest; and what is more important, they were not proved by necessary demonstrations from their primary and unquestionable foundations. Since, as I say, I want to prove these to you demonstratively, and not just persuade you of them by probable arguments… (Drake, trans., 1989, pp. 54-55)

Galileo points to the importance of what can be demonstrated or proved beyond doubt in science just as in mathematics. Notice the complaint about Aristotle's conclusions, which are "not the prettiest"; this is a reference to Galileo's preference for elegance and generality. Given that Galileo believes that science is about producing predictive mathematical models, it is consistent that interest in mathematical parsimony would translate into interest in parsimony of empirical theory.

Galileo says that reason can fill in the blank where observation is missing—this is seen for instance where Galileo reasons to mathematically regular laws based on observational data that is never *perfect*. In one sense this is akin to Aristotle's claim in *Meteorology* I.7 that, "We consider a satisfactory explanation of phenomena inaccessible to observation to have been given when our account of them is free from impossibilities" (Webster, trans., 1984, 344a5). This illustrates Aristotle's use of reason to substitute for missing observational data. There is a difference between Aristotle's statement and Galileo's using observational data as approximating mathematical laws, at least in degree of inferential leap. Galileo does not theorize about things that cannot be empirically tested.

Galileo points out that Aristotle goes farther than he does in rationally reconstructing physical phenomena, for instance as expressed by the character Simplicio when he refers to Aristotle's proof of the impossibility of void. The arguments against the possibility of the motion of the Earth were also well known (*e.g.* from Book I of Ptolemy's *Almagest*). Galileo says Aristotle's theories were not proven mathematically from unquestionable foundations. But it is not clear where these unquestionable foundations are supposed to come from or even what they are supposed to be. Of course, both Galileo and Aristotle want to find the true causes of phenomena where possible. If there is a difference between them here, it is in the ambition to pursue "phenomena inaccessible to observation" in the first place.

The difficulty of knowing how far one can reason from experience is highlighted by a brief exchange between Simplicio and Sagredo in *Two New Sciences*. Simplicio claims that common experience shows that light travels instantaneously. He gives the example of being able to see the flash from a cannon well before the sound of the shot can be heard. Sagredo must take Simplicio to task for the improper conclusion:

> From this well-known experience, Simplicio, no more can be deduced than that the sound is conducted to our hearing in a time less brief than that in which the light is conducted to us. It does not assure me whether the light is instantaneous, or time-consuming but very rapid. (Drake, trans., 1989, p. 87)

One can be deceived by sensory input if one is not careful to consider the limitations of each experience; that is, it is necessary to separate the immediate conclusions one tends to jump to as far as possible from the raw sensory data.

There is an exchange in *Two New Sciences* that shows Galileo's belief in tempering experience with reason and the Aristotelians' reluctance to apply the abstract to the material world.

> Simplicio: The considerations and demonstrations made by you up to this point, being mathematical things abstracted and separated from sensible matter, I believe would not work according to your rules if applied to physical and natural materials. (Drake, trans., 1989, p. 96)

This statement of Simplicio's describes the Aristotelian notion of observation in the material world taking precedence over the more Platonic idea of deducing the world from the ideal. Galileo answers this challenge with a conclusive demonstration using only reason to defeat Simplicio's view of free fall. Simplicio asserts the Aristotelian idea that an object ten times heavier than another object will fall ten times faster than the lighter. The character Salviati responds:

> …I seriously doubt that Aristotle ever tested whether it is true that two stones, one ten times as heavy as the other, both released at the same instant to fall from a height, say, of one hundred braccia, differed so much in their speeds that upon the arrival of the larger stone upon the ground, the other would be found to have descended no more than ten braccia. (Drake, trans., 1989, p. 106)

Simplicio makes a simplistic linguistic argument claiming that Aristotle did conduct this experiment. The heart of his argument is a quotation from Aristotle where he says, "We see the heavier…" Simplicio claims that Aristotle would not say "we see" unless he had actually conducted the experiment. Sagredo is not convinced because of the wildly different results seen at the free fall experiment in Pisa. Galileo then points out that the Aristotelian position can be defeated with reason:

> Salv: “But without other experiences, by a short and conclusive demonstration, we can prove clearly that it is not true that a heavier moveable is moved more swiftly than another, less heavy, these being the same material, and in a word, those of which Aristotle speaks.” (Drake, trans., 1989, p. 107)

What follows is a rational demonstration refuting the Aristotelian view. Simplicio first agrees to the concept of terminal velocity. He then grants that two different bodies, if “connected” would influence each other—the heavier body tending to accelerate the lighter and the lighter tending to retard the heavier. Salviati then proposes putting the two objects together thereby creating a body heavier than the larger alone. But since Simplicio agreed that the joined body should fall more slowly than the larger body alone, we have a contradiction in the theory. By Simplicio’s answer, the larger body should fall faster than the larger body joined to the smaller body because of the rule that heavier bodies fall faster. This is an absurdity, so the initial principle is false.

This is an example of Galileo using reason to show that a certain hypothesis has internal contradictions, which is one way he justifies rejecting hypotheses. However, it is crucial that he adds “without *other* experiences” before he can disprove Simplicio’s notion of free fall. This implies that some experience is necessary. Hence, the traditional characterization that the difference between Aristotle and Galileo is the difference between Rationalism and Empiricism is erroneous.[132] For both Aristotle and Galileo experience is secondary to reason.

4.7 Summary of Departure from Aristotle

So we see that Galileo differs greatly from the Aristotelians but not as dramatically from Aristotle as the standard literature portrays. When viewing Galileo's and Aristotle's works side by side, the difference is subtle but significant in four ways: (i) Galileo's greater interest in pursuing practical applications led him not to search beyond the proximate causes of phenomena and to search for the proximate causes only insofar as they help in the construction of predictive mathematical models. He does not search for the ultimate first principles and causes, which according to Aristotle, are not intended to be practically applicable (*Metaphysics* I.1). Galileo eliminates Aristotle's final and formal causes, because Galileo does not find them empirically justifiable and hence, they are an unacceptable source of error. Furthermore, (ii) Galileo does not insist that scientific explanations must answer 'why' questions, that is give the cause of the explanandum—Galileo is satisfied when he has a mathematical model that is predictive and its accuracy can be quantified. (iii) This also gives Galileo an objective standard for judging competing explanations—quantification allows for measurement of predictive accuracy. This provides a system for detecting and eliminating error from theories. Thus, (iv) whereas Aristotle seems only to be interested in explanations of phenomena, Galileo's philosophy of science is also concerned with justifcation of theory choice, e.g.

[132] For examples of this characterization see Drake (1980), Hall (1962), Reichenbach (1951), Koyré (1978); for discussions about this characterization in Galileo scholarship see Cohen (1960).

based on Ockham's razor, measurable predictive accuracy, coherence with prior theories, etc. For Galileo, once he has an explanation of a phenomenon, the explanation becomes the new explanandum that must be tested and explained. Galileo's project was not merely to furnish new scientific explanations but to change the very nature of scientific investigation.

We have now identified the point in the history of the concept of scientific explanation where Aristotle's teleological causes, which rely on identifying the essence of the explanandum, were rejected at the hands of Galileo. Now we are ready to take up the question of what would be gained and lost by trying to reintroduce the Aristotelian elements of 'essence' and 'cause' to contemporary accounts of scientific explanation.

Chapter 5. Implications for Contemporary Scientific Explanation Models

5.1 Introduction

The purpose of this thesis is to explicate Galileo's concept of scientific explanation, to illustrate how it changed from Aristotle's concept of scientific explanation, and to suggest how this analysis might be helpful to contemporary discussions of scientific explanation. Although Galileo, was not the sole agent of the Scientific Revolution, an examination of the elements of his considerable shift from Aristotle's conception of scientific explanation remains fundamental to understanding Galileo's ultimate influence on contemporary scientific explanation. As detailed in chapters 2, 3, and 4, there are marked differences between Aristotle's and Galileo's frameworks for scientific explanation, such as Galileo's increased focus on epistemic justification through mathematical modeling, as well as his use of systematic experimentation (Settle, 1998, p. 335). Discerning these differences, how and why they came about, and their importance, is essential to evaluating the merits of reintroducing into contemporary models of scientific explanation those elements that Galileo (and subsequent natural philosophers) dropped from Aristotle's account of scientific explanation (e.g., Aristotle's ideas of causation and essence).

The differences between Galileo's and Aristotle's concepts of scientific explanation are particularly topical in light of criticisms in contemporary philosophy of science that focus on the shift credited to Galileo (e.g., Brody, 1972; Van Fraassen, 1980, 1980b; Salmon, 1984, 1998). Although Galileo is not explicitly targeted, there are implicit criticisms of Galileo's exclusion of Aristotle's ideas regarding causation and essence. Specifically, these criticisms argue that the eliminated concepts of Aristotle's ideas of causation and essence should be reintroduced into contemporary science. To conclude this work, I first briefly recapitulate the primary differences between Galileo's and Aristotle's concepts of scientific explanation, particularly emphasizing the issues surrounding Aristotle's causation and essence. I then examine the arguments for reintroducing causation and essence into scientific explanation, with a contrast of Galileo's reasons for removing them. Finally, I complete this work with a summarization of the potential advantages and disadvantages of such a reintroduction.

5.2 Galileo's Actual Contributions

In this study, I have examined Galileo's and Aristotle's concepts of scientific explanation. Specifically, Galileo's ideas of scientific explanation were compared with those of Aristotle (chapter 2.5; 4.6), as well as the ideas from some of the key figures in Western science in the intervening years between Aristotle and Galileo (chapter 3.5). These comparisons show that between Aristotle and Galileo significant advancements in scientific methodology occurred, for instance, in the works of Adelard, Grosseteste, and others (chapter 3.4). Tracing the development of the theory and practice of scientific explanation from Aristotle to Galileo allows us to understand the innovations Galileo makes, as well as his motivation for those innovations.

Galileo makes two primary innovations that are relevant to our current discussion: the first consists in his increased focus on mathematical modeling; the second involves his methods of experimentation. Before reviewing these changes, it is important to point out that the root of the salient differences between Galileo and Aristotle is Galileo's insistence that science is about gaining knowledge that can be given practical application (chapter 4.2). This desire for science to have a practical use meant that predictive models were generated that could be empirically tested. If a model did not accurately predict phenomena then Galileo was forced to look for sources of error or deviation in that model. One source of error is empirical data collection. Increasing empirical justification (e.g. through experimentation) reduces error in empirical data collection. There is no such necessity for rigorous empirical justification in Aristotle's concept of science because Aristotle's aim for science is not practical application but instead an understanding of first principles. Because first principles by Aristotle's definition have the highest explanatory power and least practical applicability, Aristotle does not need the level of predictive reliability that Galileo requires that necessitated that he develop a system of more rigorous empirical justification. The differences between Aristotle's and Galileo's purposes for scientific investigation led to different approaches for achieving scientific explanations.

Examination of those differences reveals that although they are more nuanced than some previous scholarship has suggested, they are still substantial with profound impact on the pursuit for scientific explanations. What is true is that Galileo advances two intrinsically related uses of mathematics: the first is quantifying natural phenomena, and this is a prerequisite for the second, which is predicting phenomena with mathematical models. Galileo's interest in making science applicable led him to use predictive mathematical models in his concept of scientific explanation. The use of mathematical modeling allowed Galileo to explain and predict phenomena accurately in a manner that Aristotle could not, because Galileo's use of quantification allowed for more accurate model building through better testing of those models (e.g., understanding the free fall problem, chapter 4).

Another difference between Galileo and Aristotle lies in Galileo's improvement of the experimental method. Although some scholarship claims that the difference between Aristotle and Galileo is that experience was not essential to Aristotle's philosophy of science at all (Drake, 1980; Hall, 1962) while Galileo invented experimentation, in chapter 2 I show that Aristotle does care about empirical observation.[133] Further, evidence that the claim that Galileo invented experimentation is also inaccurate is demonstrated in chapter 3 where I show that scholars as early as Grosseteste were interested in experimentation. What is more correct to say is that Galileo developed a more sophisticated concept of experimentation and relied on it more rigorously than any of his predecessors had. For instance, unlike Aristotle, Galileo isolated specific variables for testing, and unlike Grosseteste, Galileo carefully designed and carried out multiple iterations of experiments. Galileo's use of the experimental method, resulting from a concern for greater empirical justification, led to more reliable results. Another result of Galileo's demand for empirical verification of his hypotheses was that he endeavored to frame only hypotheses that could be empirically tested.

[133] Much more so than Aristotle himself, it was the 17th century Aristotelians who did not care to look, e.g. in a letter he sent to Kepler, Galileo reports the absurdity the philosopher at Padua who refused to look through Galileo's telescope (Burtt, 1934, p. 66-7).

The innovations in mathematical modeling and experimentation are mutually supporting without being viciously circular, and together they form the foundation of Galileo's methodology of scientific explanation. Galileo starts with a general model, which leads to questions that he then tests using his experimental method. He then uses the results from these experiments to generate predictive models. To continue building on the internal consistency of his framework, Galileo uses the results from the predictive models to generate new questions, which are then tested through the experimental method, and so on (this is similar to the dialectic between theoretical framework and experience discussed in chapter 4).

One crucial result of Galileo's change in the focus of scientific explanation is that Galileo was not interested in pursuing Aristotle's interest in the broadest causation of natural phenomena (see chapter 2). The difference between Aristotle's search for causal explanations and Galileo's reliance on proximate causes is often characterized as involving a shift from searching for a cause (e.g., Aristotle) to searching for laws (e.g., Galileo) (Drake, 1980, p. 11). Galileo seems to have accepted that science cannot know the sort of 'why' that Aristotle sought, and is instead interested in finding proximate causes or causes only in so far as they are needed in order to create the predictive models necessary to making science applicable.

5.3 Tacit Criticisms of Galileo's Contributions

This thesis's analysis of the differences between Galileo's and Aristotle's scientific explanations starts to create a framework for examining contemporary arguments made to reintroduce into contemporary scientific explanation elements similar to Aristotle's ideas of causation. I would like to include in this framework a brief discussion of Hempel's covering law models, which are the standard for contemporary discussions about scientific explanation (Psillos, 2002; Salmon, 1984; Wallace, 1974), and which being taken into account will assist in my illustration of three criticisms posited by contemporary philosophers (this overview of criticisms is not intended to be exhaustive). While these criticisms are not identical, and there is some disagreement about the precise nature of the debate regarding contemporary scientific explanation, they share a common theme that primarily argues that explanations should address why things happen (Woodward, 2003).

Hempel's models are called "covering law" models because they require that the explanans take the form of a general law under which the particular phenomenon being explained is subsumed (Dray, 1957). The archetypical model is the Deductive-Nomological (D-N) model, which is a set of four adequacy conditions that are supposed to give the necessary and sufficient conditions for scientific explanations. The four conditions of the (D-N) model are: (i) "The explanandum must be a logical consequence of the explanans;" (ii) "The explanans must contain general laws, and these must actually be required for the derivation of the explanandum." (iii) "The explanans must have empirical content;" (iv) "The sentences constituting the explanans must be true." (Hempel and Oppenheim, 1948; Hempel, 1965). Conditions (i) and (iv) require that the explanans be valid and sound. The D-N model is nomological because condition (ii) requires that the explanans contain a general natural law. Condition (iii) requires that the explanans haves an empirical basis. These four criteria are meant to cover the full range of scientific explanations (both of general facts and particular events). These are intended to be the conditions, which taken together, are both necessary and sufficient for something to be a proper scientific explanation; however, Brody (1972) claims that these conditions are not in fact sufficient.

With Hempel's model in mind, the primary criticisms (e.g., Brody, 1972; Van Fraassen, 1980; Salmon, 1984) center on the concept that contemporary scientific explanations are missing ideas that were present in Aristotle's ideas of essence and causation, which omission erroneously allows for "scientific explanations" to lack proper explanatory power (and which omission, as stated previously, is implicitly attributable to changes in the concept of scientific explanation introduced by Galileo).

Brody (1972)

According to Brody (1972), the heart of Aristotle's notion of scientific explanation is that a demonstration that is also an explanation captures the cause of the explanandum. This account of explanation, according to Brody (1972), anticipates and resolves problems in the standard 20th century models of scientific explanation, as exemplified by the (D-N) model expressed in Hempel and Oppenheim (1948) and Hempel (1965). Specifically, Brody (1972) criticizes Hempel's (D-N) model, claiming that the model fails to establish proper explanatory power because it takes no account of two crucial elements: (i) the *essence* of the explanandum, without which one cannot be certain of (ii) the *cause* of the explanandum. If these missing elements are indeed important components of scientific explanations, then the absence of these elements in scientific explanation raises serious questions. Brody's complaint is that Hempel's models are too inclusive because although they do include intuitively satisfying accounts (i.e. those that seem to capture cause and essence) as scientific explanations, they also allow as scientific explanations intuitively unsatisfying accounts (i.e. those that seem not to capture cause and essence).

In an effort to illustrate how contemporary scientific explanation would benefit from reintroducing this discarded element of Aristotle's scientific explanation, Brody (1972) highlights the flaw he perceives in the D-N model (i.e., how criteria for an explanation can be met within the D-N model without the explanation being intuitively satisfying) by setting out the following example:

(A) (1) "sodium normally combines with bromine in a ratio of one-to-one
(2) everything that normally combines with bromine in a ratio of one-to-one normally combines with chlorine in a ratio of one-to-one
----
(3) therefore, sodium normally combines with chlorine in a ratio of one-to-one" (p. 20).

Brody says that this example reveals a problem with the D-N model because it fits the criteria for an explanation, but is intuitively unsatisfying.[134] Brody argues that it is not the case that "sodium normally combines with chlorine in a ratio of one-to-one" *because* "everything that normally combines with bromine in a ratio of one-to-one normally

[134] It can be argued that because the explanantia have empirical content and are true, Hempel's conditions (iii) and (iv) are satisfied. If we assume that conditions (i), that the explanandum is a logical consequence of the explanans, and (ii), that the explanans contain general laws that are actually required for the derivation of the explanandum, are likewise satisfied, then Brody's example would count as a scientific explanation under the D-N model. For the purpose of this thesis I assume that Brody's Explanation A does meet Hempel's conditions for a D-N explanation.

combines with chlorine in a ratio of one-to-one." Brody argues that such an explanation does not identify the cause of sodium's combining with chlorine in a ratio of one-to-one because the explanans has not captured the essential attribute of sodium that is responsible for why it combines with chlorine in a one-to-one ratio. Brody thus concludes that A is not a proper explanation. Alternatively, Brody claims that an intuitively satisfying explanation would include an account of the atomic structures of sodium and chlorine and the theory of chemical bonding, since this explanation would capture the cause and essence of sodium.[135]

In order to achieve a satisfactory solution, according to Brody (1972), one would need to add to the D-N conditions an additional condition that states "its explanans contains essentially a description of the event which is the cause of the event described in the explanandum" (p. 23). Brody claims that if this condition were added to Hempel's model, then Example A would fail to be a scientific explanation under the revised D-N model because A does not capture the essence of sodium necessary to give the cause of its combining with chlorine in a ratio of one-to-one. Brody contends that adding his new condition to Hempel's model would disqualify as D-N explanations all accounts that are not intuitively satisfying explanations, such as his Example A. Brody points out that this additional condition would, however, not disqualify accounts such as the one he suggests that includes the atomic structure of sodium and chemical bonding theory. Brody wants the model of scientific explanation to exclude all potential explanations for sodium's combining with chlorine in a ratio of one-to-one except the atomic theory explanation

[135] The atomic structure explanation would not be ruled out by the D-N model, but the point is that both Example A and the atomic structure account qualify as explanations under the D-N model.

because, presumably, atomic theory gets at the essence of sodium, and the theory of chemical bonding provides an intuitively satisfactory causal explanation of why sodium and chlorine combine in a ratio of one-to-one.

If, however, Brody's proposed addition to the set of D-N model conditions reduces the efficacy of scientific explanation models by eliminating potentially helpful explanations that scientists find useful, for example, in designing new experiments, then Brody's condition should either be qualified or disregarded. Brody's suggestion that we should accept as scientific explanations only those accounts that have intuitively satisfying elements of cause and essence would be too restrictive if it excluded potentially useful explanations. For example, in Brody's Example A, it is a valid conclusion that sodium combines with chlorine in a one-to-one ratio, and this may be useful knowledge for predictive modeling, even though this does not seem to reveal sodium's essence.

Hempel tries to avoid eliminating or restricting with his models those explanations that are actually useful in scientific inquiry. Brody, on the other hand, does not seem to be as strongly motivated to avoid eliminating potentially useful scientific tools. This illustrates another pitfall in Brody's attempt to exclude scientific explanations that are not intuitively satisfying. For instance, Hempel's covering law models allow for numerous explanations of the same phenomenon, whereas Brody's conditions may restrict the covering law explanation to one per phenomenon. As a point of comparison, take Hempel's discussion of the fact that the level of water in a beaker remains the same when an ice cube is floating as when that ice cube has melted (Hempel, 1965, p. 346).

Hempel's explanation for this is based on such laws as Archimedes' law of floating bodies, conservation of mass, etc. Explanantia of this type would naturally lead to a D-N model type explanation for the water level in a beaker with melting ice. Consequently and given the general nature of the laws used, Hempel points out that it is possible to come up with explanations governing all similar events, such as "a floating piece of marble on mercury or of a boat on water." The most direct explanation for why the beaker level remains constant while the ice melts gives us a law Hempel calls a "minimal covering law implicit in a given D-N explanation."

> But while such laws might be used for explanatory purposes, the D-N model by no means restricts deductive-nomological explanations to the use of minimal laws. Indeed such a restriction would fail to do justice to one important objective of scientific inquiry, namely, that of establishing laws and theories of broad scope, under which narrower generalizations may then be subsumed as special cases or as close approximations of such. (Hempel 1965, p. 347)

Hempel goes on to discuss the common occurrence of a D-N model explanation capturing the cause of the event. This shows that Brody's insistence that explanations capture the cause of a phenomenon is what Hempel would judge as too restrictive. Thus, Brody's suggested solution to the problems he identifies in contemporary scientific models may inadvertently weaken the applicability of scientific explanations to the actual practice of conducting science.

Brody is attempting to get at the kinds of explanations that would satisfy Aristotle's causal requirements. Hempel on the other hand, seems to be after explanations that scientists use on a day-to-day basis for experiment building. Thus, Brody is probably correct that Hempel would accept his Example A as satisfying the D-N model. Hempel might also agree that it is not as satisfying an explanation as Brody's preferred explanation involving atomic theory. However, Brody claims that his Example A is not merely less satisfying, but that it is not an explanation at all. In contrast, Hempel might argue that the fact that the atomic theory explanation applies to a more general class of phenomena does not render the first explanation useless in the design and performance of scientific experiments. However, the point of contention would remain: Hempel would claim that Explanation A is merely narrower while Brody would argue that Example A is not an 'explanation' at all.

Van Fraassen (1980a; 1980b)

Van Fraassen (1980a) joins Brody in similarly criticizing contemporary models of scientific explanation. Like Brody (1972), Van Fraassen (1980a) considers whether Aristotle's concept of scientific explanation contains elements that are missing from the standard contemporary model and further whether or not we can transfer desirable elements from Aristotle's concept of scientific explanation to contemporary models. Van Fraassen (1980a) emphasizes that the difficulties in successfully accounting for scientific explanation are the same for us as they were for Aristotle:

> [W]e can identify the main philosophical problems and puzzles concerning science that Aristotle faced, and can state them in modern terms, because we recognize them as identical or closely similar to ones we discuss today. We can also isolate, roughly, the solutions he gives. (p. 20)

Unlike Brody however, Van Fraassen pays considerable attention to the consequences (potentially unintended) of incorporating these missing elements into contemporary models of scientific explanation. Van Fraassen (1980a) summarizes his project as the quest to answer three questions that cumulatively resolve the issue of whether or not, or in what way, Aristotle's concept of scientific explanation can be mined to find solutions to some of the problems in contemporary models of scientific explanation:

> The first question for us is: how much of his account of science is just enough to solve those main philosophical problems that he and we both face? And the second question is: what is presupposed by that much of the account? And the third: could we, in good philosophical conscience, accept these presuppositions? To put it briefly: what philosophically controversial theses would have to be defended today, if we were to accept an Aristotelian account of science? (p. 20)

Van Fraassen reiterates his claim that Aristotle's "solutions are very good" particularly in his dealings with asymmetries. The asymmetry problem deals with that part of causation concerned with making sure the cause of the explanandum is captured by the explanans, and not the other way around.[136] However, Van Fraassen concludes that at the heart of

[136] To illustrate the asymmetry problem of causation consider the following examples from Aristotle's *Posterior Analytics* I. 13. First, from the terms A (being near), B (not twinkling), and C (planets), it is possible to deduce the fact of the matter:

B of C…planets do not twinkle
A of B…what does not twinkle is near
therefore, A of C…planets are near

This is a deduction of the fact of the matter that the planets are near; however, this does not answer the 'why' question because we do not think it is the case that the nearness of the planets is caused by their not twinkling. Consider the alternative deduction with the terms arranged differently; A (not twinkling), B (being near), C (planets):

B of C…planets are near
A of B…what is near does not twinkle
therefore, A of C…planets do not twinkle

This deduction is a demonstration according to Aristotle because it answers the 'why' question; i.e. the cause of the planets not twinkling is their being near.

Aristotle's solutions is what Van Fraassen calls "modal realism (the objectivity of physical necessity)." Writing about how far Aristotle goes with his inferences from observations, Van Fraassen (1980a) points out:

> Aristotle's view does not end there. The body of science consists of propositions which are necessary, according to him. And secondly, an answer to a why-question is not a good answer unless it shows why the fact at issue *had to be* the way it was. By this he means that the answer B to the question "why A?" in addition to being appropriate (that is, describing the sort of fact corresponding to the respect-in-which the question is asked) must be connected with A through a necessary truth. These necessary truths, as we saw, had to be propositions stating physical necessities, necessary connections in nature. (p. 43; original emphasis)

The condition Van Fraassen points to is Aristotle's contention that having scientific knowledge means that one knows not only why something is the case, but also that it is *necessary* that it is the case (see discussion in chapter 2.2). Having determined what we would have to accept in order to incorporate the essential elements of Aristotle's concept of scientific explanation into our own, Van Fraassen rejects the suggestion that we should include those elements from Aristotle's scientific explanation that are missing in the standard contemporary models, because to do so would necessarily mean adopting Aristotle's modal realism, which is unacceptable since it would violate basic empiricist ideas. He says, "The only genuine empiricist course at this point, it seems to me, is to deny that explaining something consists in showing why it had to be the way it is—*tout court*" (Van Fraassen, 1980, p.43).

Although Van Fraassen rejects Brody's proposal for what to borrow from Aristotle in order to improve the alleged problems in Hempel's D-N model, Van Fraassen does think there is another way that Aristotle's discussion of scientific explanation can help contemporary philosophy of science. Van Fraassen (1980a; 1980b) argues that Aristotle is right to think of explanations as answering 'why' questions. However, Van Fraassen goes further than Aristotle in that he discusses the way in which every explanation is context dependent, based on the reason any given 'why' question is asked.[137]

> The discussion of explanation went wrong at the very beginning when explanation was conceived of as a relationship like description: a relation between theory and fact. Really it is a three-term relation, between theory, fact, and context. No wonder that no single relation between theory and fact ever managed to fit more than a few examples! Being an explanation is essentially relative, for an explanation is an *answer*. (1980b, p. 156, emphasis original)

The picture of scientific explanation that Van Fraassen puts forward is very different from standard accounts because by removing the argument form and making explanations relative, Van Fraassen implies that explanation does not function as a tool that science uses to expand. Van Fraassen claims that explanations are not a part of science; instead they are a product of science. One might wonder then what the value of explanation is to science, if they are not non-relative, constructive arguments. Van Fraassen claims that, "while it is true that we seek for explanation, the value of this

[137] Van Fraassen's claim that scientific explanations are answers to questions, and as such require that the context of the question be known, is better understood through Bromberger's analysis of the presupposition of 'why' questions. Bromberger (1966) claims that every interrogative sentence has a declarative sentence as its underlying structure. Consider the following sentences: (1) "Why does copper turn green when exposed to air?" and (2) "Copper turns green when exposed to air." Bromberger uses (1) and (2) to illustrate the relationship between 'why' questions and their underlying structures; if a sentence has the relation to a 'why' question that (2) has to (1), then it is the "presupposition" of the why-question (p. 604). If the declarative sentence that is the underlying structure of the interrogative sentence is true, then it is necessary that a correct answer to the question exists. The declarative sentence indicates the presupposition of the question, which also gives the context, i.e. the presupposition indicates the context of the question.

search for science is that the search for explanation is *ipso facto* a search for empirically adequate, empirically strong theories" (p. 157, emphasis original). Instead of clarifying the distinction between explanation and theory, Van Fraassen's position raises the unanswered question of what the difference is between a strong theory and a good explanation. A fuller account is needed of why he thinks the search for explanation is *ipso facto* the search for strong theories. In general, making a distinction between explanation and theory might be useful in separating the ideas of intuitive satisfaction from applicable predictions for science. However, thinking of explanation as merely helpful in satisfying curiosity and not in advancing science is too limiting. This would seem merely to move the difficult questions about causation and essences to the discussion of scientific theories.

Salmon (1984)

Like Brody and Van Fraassen, Salmon (1984; 1998) also criticizes contemporary accounts of scientific explanation. Like Van Fraassen, Salmon is concerned that Hempel's D-N model does not address the asymmetry problem (1998, p. 101ff). Like Brody, Salmon argues that the D-N model does not, or does not properly, capture the causal aspects of explanation. Salmon supports his claim by quoting Hempel's own remarks. In "Studies in the Logic of Explanation" (1948) Hempel says that the D-N model yields "causal" explanations (Hempel, 1965, p. 250), but, Salmon points out, Hempel retreats from the claim that the D-N model explanations are causal in his (1965) reprint of and commentary on his 1948 essay.

Salmon (1984; 1998) argues that an appeal to causation is fundamental and should be a part of all scientific explanations (Salmon, 1984, p. 83).[138] To understand where Salmon's criticisms and proposed solutions lie in relation to other theories of scientific explanation, first consider how Salmon (1984) categorizes theories of scientific explanation on the basis of three 'conceptions': (1) the epistemic conception—"the event-to-be-explained was to be expected by virtue of the explanatory facts. The key to this sort of explanation is nomic expectability" (p. 16); (2) the modal conception—this gives the "nomological necessity of the fact to be explained", i.e. "given the explanatory facts it had to occur"; (3) the ontic conception—"to explain an event—to relate the event-to-be-explained to some antecedent conditions by means of laws—is to fit the explanandum-event into a discernible pattern . . .to explain an event is to exhibit it as occupying its (nomologically necessary) place in the discernable patterns of the world" (p. 18).

Salmon points out that the crucial elements of Aristotle's concept of scientific explanation can be understood in terms of all three categories. Aristotle's explanations are deductive syllogisms, so they exhibit characteristics of the epistemic conception. The modal conception is exhibited by Aristotle's second of two requirements for scientific knowledge: the first requirement is knowing that B is the explanation of A, and the second is knowing that A cannot be otherwise, i.e. knowing why it is necessary that A is the case. Finally, Salmon claims, Aristotle's account of scientific explanation exhibits the ontic conception in the necessary conditions Aristotle gives for a scientific

[138] Salmon is careful to point out that the subject being considered is scientific explanation and that his requirements for scientific explanations do not apply to all types of explanation.

explanation, such as that the explanans be causally prior to and more knowable than the explanandum.

Those elements of Aristotle's account that Salmon thinks should be incorporated into contemporary models are the elements that place Aristotle's account in the ontic conception category. These are also the elements of Salmon's proposal to improve covering law models that are relevant to this discussion. I do not consider the details of Salmon's probabilistic causal-relation model. Instead, I am concerned generally with the potential pitfalls of reintroducing elements of Aristotle's theory of explanation into contemporary models. Salmon describes how his preference for the ontic conception is different from Hempel's D-N model of explanation. Salmon (1984) summarizes the difference between his view and Hempel's as follows:

> The *ontic conception* is the one for which I shall be arguing. In Salmon (1977: 162), I offered the following characterization: 'To give scientific explanations is to show how events…fit into the causal structure of the world.' Hempel summarizes the import of his major monographic essay, 'Aspects of Scientific Explanation' (1965a: 488), in rather similar terms: 'The central theme of this essay has been, briefly, that all scientific explanation involves, explicitly or by implication, a subsumption of its subject matter under general regularities; that it seeks to provide a systematic understanding of empirical phenomena by showing that they fit into a nomic nexus.' I find this statement by Hempel in almost complete accord with the viewpoint I shall be advocating; my suggestion for modification would be to substitute the words '*how* they fit into a *causal* nexus' for '*that* they fit into a *nomic* nexus'. (p. 82; emphasis original)

In short, Salmon (1984) is arguing that his model is very close to Hempel's, but that Hempel's model would be improved if explanations revealed details about the causal relationships among phenomena being explained including how new phenomena fit in the scheme of all previously explained phenomena. Explaining phenomena in terms of how they fit into the broadest causal picture is the feature of Aristotle's model of scientific explanation that Salmon believes should be present in contemporary models.

Salmon (1984) is well-aware of the potential difficulties of trying to give causal explanations.

> In view of well-known Humean problems associated with causality, it might *seem* desirable to try to avoid reference to causal laws in dealing with scientific explanation. Nevertheless, I shall try to show that we need not purge the causal notions; indeed, I shall argue that they are required for an adequate theory of scientific explanation (p. 83; emphasis original).

Salmon (1984) argues for the ontic conception, and ultimately for a probabilistic theory of causality (p. 43). He argues that adding a causal relation component to statistical relevance models could solve some of the problems of contemporary models of scientific explanation such as the asymmetry problem that is dealt with by Aristotle.[139,140]

5.4 These Criticisms of the Standard Model Are Due to Galileo

There are, however, some difficulties with adopting a theory of scientific explanation that falls under Salmon's ontic conception, and some of these problems parallel the difficulties associated with implementing Brody's suggestions. Recall that Galileo does not reject all causal explanations, but he focuses on the 'proximate' cause

[139] See discussion of asymmetry problem in the Van Fraassen section, above.

[140] Salmon believes that causation is needed to correct the problems with Hempel's models because identifying general laws does not guarantee that one has captured causation. Salmon (1984) points out that the 'general law' that night follows day follows night, etc., fails to establish a causal relation because we do not think that day causes night or night causes day (p. 135). Hempel would argue that this is not a problem because the law still works.

and rejects Aristotle's idea of causation. Salmon tries to reconcile these differences by taking Aristotle's idea of causation and changing it to make it probabilistic.

Despite adding an element of probability, Salmon's interest in determining causation still represents a meaningful departure from Galileo's concept of scientific explanation. This is because even Salmon's probabilistic models of causation require a substantial reliance on non-empirical factors such as intuition, although perhaps not as dramatically as in the case of Brody's model. Brody and Salmon are aware that the notion of causation they are trying to put into their models requires capturing the essence of the thing being explained. I will show below why the determination of essences relies on what I will argue is too strong a component of intuition. As demonstrated throughout the history of science, intuitions, particularly very strong intuitions, can inhibit scientific advancement. For example, we have strong intuitions that the Earth is not moving, and only through empirical science have we demonstrated that this intuition is incorrect. Relying too heavily on intuition as the final judge to determine the right explanation is problematic because breakthrough scientific explanations are frequently in contradiction with some apparently fundamental intuitions.

In contemporary philosophy of science, one way to characterize the search for natural laws is as the search for regularity (e.g., Salmon, 1998; Hempel, 1965). This search for regularity may be directly tied to the shift in science that Galileo makes from searching for Aristotle's causes to searching for laws (Drake, 1980).[141] Galileo says that to understand something means to be able to comprehend it with mathematical

[141] See chapter 4.3 – for Galileo, searching for 'laws' includes searching for the 'proximate' cause.

regularity.[142] Galileo's account of scientific explanation, which is perfectly consistent with covering law models, is focused on identifying regularity, which in itself does not provide a means for dealing with the asymmetry problem. Thus, Galileo is, in part, responsible for the asymmetry problem that Brody, Van Fraassen, and Salmon point to in contemporary covering law models.

5.5. Why Some Proposed Resolutions of these Criticisms May Be Undesirable

One purpose of this thesis is to show that an examination of the changes in accounts of scientific explanation from Aristotle to Galileo could be used to create a framework within which one may evaluate the criticisms of contemporary models of scientific explanation, such as Hempel's covering law models, as well as evaluate the proposed solutions to the problems identified by these criticisms. To show that the investigations in chapters 2, 3, and 4 can be helpful in understanding the types of criticisms exemplified by Brody (1972), Van Fraassen (1980a), and Salmon (1984), I apply my framework and show that implementing some of the solutions offered may lead to a reduction in empirical rigor of scientific explanations that is inconsistent with a reasonable empiricism. What follows is only a sketch of how such an analysis might proceed, and further development is needed to reach more definitive conclusions.

The focus of this thesis's treatment of Galileo is on precisely how he was able to provide an improved model for scientific explanation by rejecting certain elements of

[142] See Galileo's discussion of the connection between understanding and mathematical regularity in *The Assayer* (Drake, 1957, p. 240-241) and his discussion of free fall in the *Dialogue*, "Second Day" (Drake, 1981, p. 236).

Aristotle's approach. He implemented these changes in large part to increase the applicability and efficacy of science. The most significant differences between Galileo's and Aristotle's models of scientific explanation, relevant to criticisms of contemporary models of scientific explanation are: first, in generating universals from empirical observations Galileo requires empirical verification of a particular type (i.e. experimentation) for his hypotheses that Aristotle does not require for his own. And second, Galileo refrains from making higher order hypotheses that cannot be empirically tested while Aristotle continues to reason from first order universals to higher and higher order "explanatory" principles. Specifically, Galileo argues that science should not deal in empty 'formal' explanations of the Aristotelian type because they do not really explain anything. Galileo rejects making those inferences that would be required for the kinds of assertions about Aristotelian causes and essences that Brody (1972) and Salmon (1984) claim are components of proper scientific explanations.

Brody (1972), Van Fraassen (1980a), and Salmon (1984) have different criticisms of, and proposed improvements to, the standard scientific explanation models. However, although none of them specifically states it, their basic criticisms as discussed here amount to an attack on Galileo's contributions to scientific explanation. Next, I explain why accepting the kind of improvements proposed by Brody and Salmon may require that we sacrifice some of what was gained by Galileo.

Brody and Salmon attempt to solve the asymmetry problem they identify in covering law models by supplementing contemporary models with conditions that are intended to capture the causal relations between the explanans and the explanandum in a manner similar to Aristotle's model of causation. This sense of Aristotelian causation that Brody and Salmon propose requires that the essential attributes of the explanandum be identified.[143] Van Fraassen argues that the proposed solutions come at too high a price for empiricism. He determines that requiring that scientific explanations capture essences entails: (i) a strong form of 'modal realism' because searching for essences implies the metaphysical commitment to there being such things as essential attributes; and (ii) that we could discover these essential attributes through scientific investigations. Van Fraassen's objection stems from the notion that making determinations about essences is inconsistent with a reasonable empiricism. I argue that making essentialist claims is incompatible with a reasonable empiricism because statements about essential attributes cannot be empirically tested or falsified, and are thus inconsistent with a reasonable empiricism.

If Van Fraassen is right about the minimum metaphysical commitment necessary to adopt these proposed solutions, and if they are indeed inconsistent with a reasonable empiricism, then these solutions should be rejected. For Van Fraassen's argument to be convincing, we have to show, first, that the types of explanation that Brody and Salmon want entail a commitment to modal realism, and second, that this form of modal realism is inconsistent with a reasonable empiricism. To show that searching for essential attributes, in the manner suggested by Brody and Salmon, requires adopting modal

[143] According to Aristotle, in order to qualify as a scientific explanation the deduction must capture the cause of the explanandum. His conditions require that the cause of the explanandum being captured explain an essential attribute of the explanandum because there are not universal causal principles of accidental attributes. Thus, it is not possible to give a scientific explanation that uses Aristotle's sense of causation unless one commits to the existence essences and to our ability to correctly identify essences. (See chapter 2.2) This commitment to essences is acceptable and perhaps desired by Brody and Salmon and it is what I am arguing violates a reasonable sense of empiricism.

realism, first I show that Aristotle's approach to the asymmetry problem relies on determining the causal relations between the explanans and the explanandum through the essential attributes of the subject of the explanandum. Second, I show that we cannot determine cause and essence without a commitment to modal realism.

Aristotle's account of scientific explanations solves the asymmetry problem by not allowing deductions to qualify as scientific explanations if they do not capture the causal relations between the explanans and the explanandum primarily by identifying the essential attributes of the subject of the explanandum. That the way Aristotle deals with the asymmetry problem requires identifying causes and essences can be illustrated by the two deductions presented in *Posterior Analytics* I.13 involving the non-twinkling of the planets. [144] "Planets", "near", and "not twinkling", can be arranged such that they produce two different deductions with two different explananda. First, the explanandum "the planets are near" deductively follows from the premises "the planets do not twinkle" and "what does not twinkle is near." The second explanandum is: "the planets do not twinkle." Taking the converse of the premise "what does not twinkle is near" yields "what is near does not twinkle." The second explanandum deductively follows from this premise ("what is near does not twinkle") and the premise "the planets are near." Although both conclusions are deductions, only the second deduction satisfies Aristotle's criteria for a scientific explanation. The first deduction is not an explanation, according to Aristotle, because he does not think it is the case that the planets are near *because* they do not twinkle. Aristotle claims that the second deduction on the other hand, does

[144] See footnote 136 in this chapter for more discussion of this example.

capture the cause of its explanandum: the reason 'why' the planets do not twinkle is that they are near. It is worth noting that neither deduction captures the cause of the planets' nearness.[145] However, the second deduction does capture the cause of the phenomenon of the planets not twinkling, and so satisfies Aristotle's account of scientific explanation, and hence has solved the asymmetry problem.[146]

Van Fraassen argues that making assertions about Aristotelian causes and essences, however, requires the metaphysical commitment of modal realism. Essential attributes are those attributes that are not accidental; that is to say, essential attributes cannot be other than they are – they are necessarily the case. Van Fraassen argues that essentialist claims are inconsistent with empiricist methodology. In principle, what empirical scientific methods, i.e. rigorous experimentation, can provide is data that suggests generalizations about which attributes of a given substance are universally concomitant to the substance and which attributes are not (where universally concomitant attributes are those attributes that are always present when a given substance is present).[147] Even though these generalizations are susceptible to the induction problem, they are nevertheless consistent with empiricism because they suggest how they can be tested; further these kinds of generalizations make clear just what empirical data could

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[145] The second deduction is a scientific explanation in Aristotle's judgment, even though the planets' not twinkling does not seem to be an essential attribute of the planets (i.e. if they were suddenly removed to a great distance from Earth, presumably we would observe them twinkling and presumably Aristotle would still think they are planets. The problem with this from a contemporary perspective is that the planets' being planets in the descriptive sense of "wanderers" is directly tied to their nearness insofar as they must be near in order to orbit around the same star that Earth does. However, for the argument here I assume that Aristotle would assume that the planets would retain their apparent behaviors even if farther away.

[146] Aristotle says that sometimes negative facts can be causes of phenomena, e.g., the ship foundered because the pilot was missing.

[147] In fact, this is a role that experimentation plays by design insofar as experiments isolate variables testing and measure correlations.

falsify the generalizations. Van Fraassen argues that in order to make generalizations about essential attributes, however, it must be possible to distinguish from among the set of universally concomitant attributes those that are universal and essential from those that are universal and accidental. Following Brody (1972) who cites Aristotle, Van Fraassen (1980a) accepts that essential attributes are necessary attributes (though the converse does not hold). Hence, in Aristotle's account, that there be necessary attributes is a necessary condition of there being essential attributes. Van Fraassen points out that if one reduces the problem of differentiating essential attributes from accidental attributes to the problem of differentiating necessary attributes from contingent attributes, the same empirical problem remains: there is no clear empirical test by which we could distinguish from among the universally concomitant attributes those attributes that are universal and necessary from those that are universal and contingent.

Going beyond making generalizations that claim what is the case in nature to making generalizations about what is necessarily the case in nature entails modal realism. Simply put, claiming about an attribute of a natural kind that it cannot be otherwise is making a modal realist determination. The commitment to modal realism is evident in Aristotle's account of scientific explanation because explanada that hold only contingently cannot be matters of scientific knowledge. To be an object of scientific knowledge for Aristotle, the explanandum must hold necessarily. The necessity of the explanandum is ensured by knowing the essence and cause of the explanandum; i.e., knowing that you have the essence and cause of the explanandum means knowing that the explanandum could not have failed to be as it is.

Having established that modal realism is an inherent prerequisite for accepting those elements of Aristotle's system that solve the asymmetry problem, Van Fraassen explains why he thinks adopting modal realism is inconsistent with a reasonable account of empiricism. Van Fraassen (1980a) argues that if there is 'physical necessity' in the world then, "it must be possible to conceive of three distinct eventualities":

> 1. law X holds (X is necessarily the case in the world, the world is subject to X)
> 2. law X does not hold, and is in fact violated
> 3. law X does not hold, yet is never violated.
>
> It must be possible, in other words, to conceive of distinct possible worlds which are exactly alike with respect to their inhabitants and what happens to them – in the one with necessity, in the other accidentally. (p. 41)

Here Van Fraassen illustrates why modal realism is a problem for empiricism. The experimental and observational methods of contemporary empirical sciences can only ask questions that can be answered by empirical data. The distinctions one must draw among phenomena that modal realism requires are inherently beyond what can be determined by empirical methods, and thus assertions about essences are lacking empirical content.

Van Fraassen claims that the only way one could empirically make sense of the notion of 'necessary' attributes would be if one were to define necessary attributes strictly in terms of universally concomitant attributes. Hence, 'universally concomitant contingent' would simply not be a category in this scheme because what it means to be a necessary attribute would be cashed out in terms of universal concomitancy. If one rejects this understanding of 'necessary' attribute (as Brody does) then Van Fraassen argues that one is left with the following challenge:

> If a world without a necessary connection between two things, is simply one in which the two do not always go together – then the two are necessarily connected if, and only if, they are connected in fact. And so, a universal proposition would be necessary if and only if it were true. The distinction collapses. Similarly if we could only know that two things are not necessarily connected by seeing them separate in fact, the empirical investigation of necessities seems indistinguishable from an inquiry into mere regularities. (p. 41)

Here Van Fraassen is arguing that if modal realists try to give empirical content to statements of 'physical necessity' by reducing them to statements about universally concomitant attributes then they would have to show how their pursuit is anything other than the search for physical regularities. Comprehending physical regularities is the aim of covering law models and this aim is precisely what Brody claims is inadequate.

Brody (1972) anticipates Van Fraassen's objection that adopting elements from Aristotle into contemporary models requires accepting metaphysical commitments that are not empirically justifiable. Brody (1972) says:

> The trouble with this objection is that it just assumes, without any arguments, that claims about the essences of objects would have to be empirically undecidable claims, claims that could be decided only upon the basis of metaphysical assumptions. This presupposition, besides being unsupported, just seems false. (pp. 26-27)

Here Brody argues that the objection that essentialist explanations require a "metaphysical assumption" component, such as intuition, is unsupported and seems false. However, given Brody's (1972) claim that essential attributes are necessary attributes (p. 25), Van Fraassen (1980a) supports his claims about the metaphysical commitments necessary to make assertions about causation and essence by pointing out in the earlier quotation that the world where everything happens without necessity is empirically indistinguishable from another world where the same events happen but with necessity. Brody offers an initial solution to the problem of how we can come to know which attributes are essential to a given body. Consider again Brody's test case: one necessary attribute of sodium is that it has atomic number 11; another necessary attribute of sodium is that it combines with bromine in a ratio of one-to-one (Brody, 1972, p. 25). Brody argues that the atomic structure explanation captures the essence of sodium and that the combining attributes explanation does not because: "One can, after all, imagine situations in which it would not combine in that ratio but in which it would still be (numerically) the same object" (p. 25). It seems that all one would have to do to refute an argument based on imagination, such as Brody's, would be to imagine a situation in which the combining attributes of sodium held but its atomic number was changed and in which it remained sodium.[148] Van Fraassen points out that the physical necessity Aristotle is talking about does not bind our imagination; it only binds nature (p. 40). By this Van Fraassen means that it is possible to accept Aristotle's metaphysical commitment to 'physical necessity' while imagining something that is not possible in the actual world: "we can imagine that the vine is not necessarily deciduous – while recognizing that perhaps it is" (p. 40). Van Fraassen is making the point that Aristotle did not think that imagination was a test that could reveal necessary truths about natural kinds. Furthermore, if Brody intends for imagination to be the test that determines essences,

[148] The argument here is not about stipulative definitions. Neither I nor Brody wants to claim that atomic number 11 is essential to sodium because we have defined sodium to be that element with atomic number 11. The issue about determining its essence is not about the word "sodium". Brody is arguing that we can get at the essential attributes of that substance that we call "sodium".

then he would have to concede that statements based on imagination/intuition are not straightforwardly empirically testable, which is Van Fraassen's objection.[149] They are also in an obvious way subjective.

A potential counterargument to Van Fraassen's objection is found in Kripke's *Naming and Necessity* (1980), where Kripke claims that essential attributes are determined empirically and not *a priori* (p. 125 ff). The point being made by Van Fraassen, which I support, is that among the empirically discovered attributes of natural kinds that are universally present, the determination of which universal attributes are the essential ones is not one that can be made on the basis of empirical testing such as experimentation. Of course it is the case that all of the attributes that we know of were determined empirically. For instance, in the case of sodium, the fact that sodium turned out to be the element with atomic number 11, that it has the position it does on our periodic tables, that sodium combines with bromine in a ratio of 1:1, etc., and in fact all of sodium's universally concomitant attributes were determined empirically. The point being made here is that the determination of which empirically-discovered attributes are essential and which are not essential cannot be made empirically.

To reconcile the competing ideas of Brody and Van Fraassen, I propose an alternative way to think about 'essential' attributes which has the advantage of giving essentialist claims empirical content, but with the disadvantage that this reduction of essentialism will not be intuitively satisfying to die-hard essentialists, such as Brody, who

[149] Brody later claims about essences that it is simply a fact that we know which attributes are essential even though we do not know how we know them (p. 30). However, Brody's assertion that we do know the essential attributes fails his model of explanation.

insist that human intellect is able to identify essences even if the epistemology of such identification cannot be explained. I propose that we could think of what Brody would call ‘essential’ attributes as those universally concomitant attributes that are more general (i.e. apply to a larger class of phenomena) in their explanatory scope than the other universally concomitant attributes of a given phenomenon. The advantage to adopting this notion of essence is that we could use empirical methods for determining essence. For example, through experimentation we can show that the atomic structure of sodium is a universally concomitant attribute of sodium. Likewise, we can show that another universally concomitant attribute of sodium is that it combines with bromine in a ratio of one-to-one. We call these attributes of sodium universal because if we had a test sample in which either one of these attributes was not detected, we would conclude that the test sample was not sodium. If all the universally concomitant attributes of a given body were considered to be its essential attributes, then sodium’s combinative attributes would be essential attributes.

In the generality conception of essence we can identify the atomic structure attribute of sodium as providing a unifying explanation in the sense that the atomic structure attribute might also explain other attributes. Redefining ‘essence’ this way could lead to strange sounding locutions; for instance, on this approach one could say that the atomic structure attribute is *more essential* than sodium’s combinative attributes because the atomic structure attribute seems to encompass other attributes such as the combination attributes.[150] However, Brody (1972) rejects thinking of ‘essence’ in terms of explanatory generality. He asks rhetorically: “why should laws that explain more explain better?” (p. 21). Brody claims that there is no necessary connection between generality of explanatory power and getting at essences. If ‘essence’ cannot be understood in terms of greater generality then I argue that we have not adequately solved the problem, identified by Van Fraassen, that searching for ‘essences’ and ‘causes’ would pose for a reasonable empiricism.

The benefit of making essentialist claims about natural phenomena seems to be greater intuitive satisfaction. However, Feynman (1965) points out that the more general physical laws become the more mathematically complex and less intuitively satisfying they become, e.g. laws of quantum electrodynamics (p. 39). Galileo claims that Copernicus’ genius was that he was able to make reason conquer sense (*Dialogue*, p. 381). Galileo is arguing that science must accept even intuitively unsatisfying explanations, such as Copernicus’ and Feynman’s in order to advance. I argue that one important lesson we can take from Galileo is that, although one’s metaphysics, such as expressed by intuition, plays a fundamental role in empirical science, e.g. in influencing which questions one thinks need answering (see chapter 4.6), one’s metaphysics should not be used as the final judge in theory building: empirical justification is more reliable

[150] This proposed redefinition of ‘essence’ in terms of empirically determinable attributes is consistent with, but does not goes as Causey (1977) in terms of defining a clear empirical hierarchical relation among attributes. Causey is able to eliminate essentialist language altogether by explaining the increases in our understanding that come from realizations such as that atomic attributes of sodium seem to encapsulate its combination attributes, in terms of “microreductions”. Mircoreductions allow for the above proposed generality relation of ‘essential’ attributes but are much broader. Causey proposes that possible microreductions might include whole groups of theories instead of merely looking at attributes of substances; e.g. biology to chemistry and physics, thermodynamics to statistical mechanics (p. 49).

than justification based on metaphysical commitments. For this reason, I propose the following rubric, which I discuss in chapter 4 as the necessary dialectic between experience and theory: theoretical framework (including intuition) $\longrightarrow$ experimental observations $\longrightarrow$ revised theoretical framework $\longrightarrow$ new experimental observations $\longrightarrow$ etc. And further that, given good experimental method, robust results, etc., we resist adding non-empirical claims to the data based on the condition of intuitive satisfaction.

Cartwright (1983) claims that there are two different goals for scientific theories: (i) knowing what is the case in nature and (ii) knowing how to explain it. Aristotle counsels us to, "like archers who have a mark to aim at," let the goal of any inquiry determine the method for achieving that goal.[151] Hence, with respect to the second of Cartwright's goals, we should further consider what the goal of scientific explanations ought to be. If the goal is, like Galileo's, to generate useful predictive models by finding laws of nature, then I argue that my preliminary framework suggests that we are better off not undermining Galileo's rejection of certain elements of Aristotle's notion of scientific explanation.

[151] *Nicomachean Ethics* I.3, Ross, trans., 1980, 1094a19

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